THE ASTRONOMICAL JOURNAL, 121:1050–1070, 2001 February

THE PROGENITOR MASSES OF WOLF-RAYET STARS AND LUMINOUS BLUE VARIABLES DETERMINED FROM CLUSTER TURNOFFS. II. RESULTS FROM 12 GALACTIC CLUSTERS AND OB ASSOCIATIONS

PHILIP MASSEY[1,2]
Kitt Peak National Observatory, National Optical Astronomy Observatories, P.O. Box 26732, Tucson, AZ 85726-6732; massey@lowell.edu

AND

KATHLEEN DEGIOIA-EASTWOOD[3] AND ELIZABETH WATERHOUSE[3,4]
Department of Physics and Astronomy, Northern Arizona University, P.O. Box 6010, Flagstaff, AZ 86011-6010; kathy.eastwood@nau.edu, waterh@fas.harvard.edu
Received 2000 September 27; accepted 2000 October 31

ABSTRACT

In a previous paper on the Magellanic Clouds, we demonstrated that coeval clusters provide a powerful tool for probing the progenitor masses of Wolf-Rayet (W-R) stars and luminous blue variables (LBVs). Here we extend this work to the higher metallicity regions of the Milky Way, studying 12 Galactic clusters. We present new spectral types for the unevolved stars and use these, plus data from the literature, to construct H-R diagrams. We find that all but two of the clusters are highly coeval, with the highest mass stars having formed over a period of less than 1 Myr. The turnoff masses show that at Milky Way metallicities some W-R stars (of early WN type) come from stars with masses as low as 20–25 $M_\odot$. Other early-type WN stars appears to have evolved from high masses, suggesting that a large range of masses evolve through an early WN stage. On the other hand, WN7 stars are found only in clusters with very high turnoff masses, over 120 $M_\odot$. Similarly, the LBVs are only found in clusters with the highest turnoff masses, as we found in the Magellanic Clouds, providing very strong evidence that LBVs are a normal stage in the evolution of the most massive stars. Although clusters containing WN7 stars and LBVs can be as young as 1 Myr, we argue that these objects are evolved, and that the young age simply reflects the very high masses that characterize the progenitors of such stars. In particular, we show that the LBV η Car appears to be coeval with the rest of the Trumpler 14/16 complex. Although the WC stars in the Magellanic Clouds were found in clusters with turnoff masses as low as 45 $M_\odot$, the three Galactic WC stars in our sample are all found in clusters with high turnoff masses (>70 $M_\odot$); whether this difference is significant or due to small number statistics remains to be seen. The bolometric corrections of Galactic W-R stars are hard to establish using the cluster turnoff method but are consistent with the "standard model" of Hillier.

Key words: open clusters and associations: general — stars: early-type — stars: evolution — stars: Wolf-Rayet

1. INTRODUCTION

1.1. *Background*

Massive, luminous stars begin their hydrogen-burning lives as hot, O-type stars. During their main-sequence evolution (2.5–8 Myr for stars with initial masses of 120–20 $M_\odot$), they may lose a significant amount of their mass as a result of strong stellar winds. The observed mass-loss rates suggest that the highest mass stars will lose as much as half their mass during the H-burning stage. Since these winds are driven by radiation pressure through highly ionized metal lines, the mass-loss rates will increase with stellar luminosity, metallicity, and effective temperature. It was Conti (1976) who first suggested that mass loss provided a simple explanation for how Wolf-Rayet (W-R) stars form. In the modern version of the "Conti scenario" (Maeder & Conti 1994), this mass loss results in a stripping off of the H-rich outer layers of the star, resulting in a WN-type W-R star, in which the H-burning products (He and N) are enriched at the surface, with strong, broad emission lines indicative of enhanced stellar winds forming an extended atmosphere. Most WN stars are presumed to be He-burning objects, although there is evidence that a few H-rich late-type WN stars are still near the end of the core hydrogen burning phase (Conti et al. 1995). Further mass loss and evolution reveals the products of He burning (C and O) at the surface, and the star is spectroscopically identified as a WC-type W-R star.

It is possible that the highest mass stars also go through a luminous blue variable (LBV) stage on their way to becoming W-R stars, with the large, episodic mass loss that characterizes LBVs aiding the process. Stars of slightly lower luminosity (mass) will not have an LBV phase, but recent observations (Massey 1998b) suggest that they do go through an intermediate red supergiant (RSG) phase, even at moderately high metallicities, albeit for a short time. At some lower luminosity, one expects that the mass-loss rates are sufficient to produce a WN-type W-R star, but not a WC; at even lower luminosities, mass-loss rates are so low

[1] Current address: Lowell Observatory, 1400 West Mars Hill Road, Flagstaff, AZ 86001.
[2] Visiting Astronomer, Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatories (NOAO), operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
[3] Visiting Astronomer, Kitt Peak National Observatory, NOAO.
[4] Participant in the NSF's Research Experiences for Undergraduates program, summer 1998. Current address: Harvard University, 436 Eliot House Mail Center, 101 Dunster Street, Cambridge, MA 02138.

that the He-burning stage is spent entirely as an RSG and not as a W-R star.

In this version of the "Conti scenario," we thus might expect the following "paths" to be followed, in order of decreasing luminosities:

$$\mathrm{O} \rightarrow \mathrm{LBV} \rightarrow \mathrm{WN} \rightarrow \mathrm{WC}\ , \qquad (1)$$

$$\mathrm{O} \rightarrow \mathrm{RSG} \rightarrow \mathrm{WN} \rightarrow \mathrm{WC}\ , \qquad (2)$$

$$\mathrm{O} \rightarrow \mathrm{RSG} \rightarrow \mathrm{WN}\ , \qquad (3)$$

$$\mathrm{OB} \rightarrow \mathrm{RSG}\ . \qquad (4)$$

The masses corresponding to these paths are unknown (and indeed we are unsure even of the qualitative correctness of these paths), but "standard guesses" for characteristic values would be (1) $\geq 80\ M_{\odot}$, (2) 60 $M_{\odot}$, (3) 40 $M_{\odot}$, and (4) 20 $M_{\odot}$, respectively. We emphasize that these are purely speculative values, and that the actual ranges should depend upon metallicity. Indeed, it is to address this issue that the present series of papers has come about.

Between the initial O-type stage (of luminosity class V) and the He-burning stage (LBVs, W-R stars, RSGs), the star will become a B-type supergiant; most, but not all, of these are expected to still be H-burning objects (Massey et al. 1995b). The luminous A–F supergiants are very short-lived intermediate stages during He burning for stars of intermediately high mass, depending upon the metallicity. The precursor to SN 1987A is believed to have been a "second generation" B-type supergiant, an He-burning object of somewhat lower mass than those being discussed here.

In addition to the question whether the above paths are correct, and what masses to assign to each as a function of metallicity, we are also interested in the evolutionary significance, if any, of the Wolf-Rayet spectral subtypes. WN-type W-R stars are classified as "early" (WNE) or "late" (WNL) depending on whether N V $\lambda\lambda$4602, 4619 or N III $\lambda\lambda$4634, 4642 dominates; i.e., WNE stars correspond to numerical subtypes WN2, WN3, WN4, while WNL stars consist of subtypes WN6, WN7, WN8, and WN9, with the WN5 stars split between the two groups. Similarly, WC-type W-R stars are classified as WCE or WCL depending upon whether C III λ5696 dominates over C IV λ5808; i.e., corresponding to spectral subtypes WC4 through WC6 and WC8–WC9, with some WC7 stars falling into each camp (Conti & Massey 1989). Do these subtypes mean anything in an evolutionary sense? Various authors have claimed so (see, e.g., Moffat 1982), but this conjecture does not seem to be borne out by either observational or theoretical studies.

Our understanding of massive star evolution is limited, in part, because of the difficulty of constructing stellar models from first principles. The physics of massive stars is complicated by strong stellar winds, and the choice of the functional dependence of mass-loss rates on stellar parameters (luminosity, temperature, mass, and metallicity) greatly influences the theoretical tracks (see, e.g., Meynet et al. 1994), particularly in the later stages of evolution. In addition, the models are sensitive to the amount of mixing. However, there is little agreement on the treatment of the relevant processes of semiconvection and overshooting (Maeder & Conti 1994), while the most recent work has emphasized the significant role that rotation may play in this regard (Maeder 1997, 1999). Nevertheless, empirical studies of massive star evolution provide confidence that the above picture is correct, and they are beginning to provide quantitative information on the mass ranges corresponding to the various paths. These studies provide an observational basis against which the models can be evaluated and refined (for a humorous rendering of this process, the reader is referred to Fig. 5 in Conti 1982).

1.2. *An Observational Approach*

1.2.1. *Global Studies*

The galaxies of the Local Group provide perfect laboratories for pursing these studies observationally, as the metallicity differs by almost an order of magnitude (SMC to M31) among the galaxies currently active in forming stars. During the past few years there have been a number of studies of *mixed age* populations, the relative number of *this* and *that*. The implicit assumption of these studies are that the initial mass function (IMF) slopes are identical and that such studies cover regions that provide a good sampling of stellar stages over time. The number ratios provide a quantitative criterion for the models to attempt to match. These studies have found the following:

1. The number of RSGs relative to W-R stars decreases with increasing metallicity (Massey 1998b; Massey & Johnson 1998). Histograms of the number of RSGs versus luminosity reveal that there are proportionately fewer high-luminosity RSGs at higher metallicity, while the lack of a sharp luminosity cutoff supports the interpretation that as Z increases, massive stars spend a greater fraction of their He-burning phase as W-R stars, and a smaller fraction as RSGs, rather than there being a difference in the actual mass ranges that go through an RSG phase. This is why we indicated an RSG phase at high luminosities (path 2 above). Possibly even LBVs will go—or have gone—through an RSG phase, but this is unknown. We also do not know whether massive stars go through an RSG phase at the highest metallicities: the relation between the RSG/W-R ratio and metallicity appears to flatten below the high metallicity that characterizes M31, but only a few regions have been surveyed in that large galaxy, and more data are being gathered to resolve this.

2. The relative number of WC to WN stars increases with increasing metallicity, with the notable exception of the starburst galaxy IC 10 (Fig. 8 in Massey & Johnson 1998). This trend is also in accord with the predictions of the Conti scenario, as increased mass loss makes it possible for a star of a given luminosity to reach the WC stage sooner, spending more of its W-R stage as a WC rather than a WN star. (The explanation for IC 10's peculiarly high WC/WN ratio remains a mystery at present; see discussion in Massey & Johnson 1998.)

3. Significant differences in the spectral subtypes found in the Magellanic Clouds compared with the Milky Way were noted by Smith (1968): no WCL stars are found in the LMC or SMC, and most of the ones known in the Milky Way are found inward of the solar circle. Similar differences are seen for the WN stars. Armandroff & Massey (1991) showed that the WC line widths (which are correlated with spectral subclass) change systematically with metallicity, extending an important finding by Willis, Schild, & Smith (1992) to other galaxies of the Local Group. Massey (1996) proposed that the WC spectral subtypes are nothing more than an atmospheric effect due to metallicity (see also Massey & Johnson 1998). Recently, Crowther (2000) has demonstrated from Wolf-Rayet model atmospheres that the WN

subtypes may similarly be a reflection of metallicity rather than other stellar parameters, at least in terms of WN3 through WN6.

1.2.2. *Coeval Associations*

A more direct way exists to attack the problem of understanding massive star evolution. By using coeval associations that contain evolved, massive stars, we can in fact directly *measure* the mass ranges that correspond to the above evolutionary paths as a function of metallicity. This is the subject of the current series of papers.

In Paper I of this series (Massey, Waterhouse, & DeGioia-Eastwood 2000), we established that many Magellanic Cloud OB associations and young clusters are sufficiently coeval ($\Delta\tau < 1$ Myr) that we can measure a meaningful cluster turnoff mass, i.e., the mass of the most massive star on the main sequence. These turnoff masses then place a lower limit on the mass of the progenitors of the evolved stars in the cluster, to the extent that star formation proceeded coevally. If the cluster is well populated, then the initial mass of the turnoff star is a good approximation to the initial mass of the progenitor of the W-R star. In addition, the bolometric luminosity of the cluster turnoff sets useful limits on the bolometric corrections for the evolved stars, allowing tests of Wolf-Rayet model atmospheres, such as Hillier's "standard model" (Hillier 1987, 1990).

The results were quite revealing. In a study of 19 OB associations in the Magellanic Clouds, we found that at the low metallicities that characterize the SMC, only the highest mass stars ($>70\ M_\odot$) become W-R stars, although the sample is small. This is equivalent to saying that path 3 above occurs only for $M > 70\ M_\odot$ for $Z \leq 0.005$.[5] At the higher metallicity of the LMC ($Z = 0.008$), WN W-R stars come from stars with masses as low as 30 $M_\odot$. We also found that WC stars are found in the same clusters as WNE stars; e.g., the lowest turnoff mass found for a cluster containing WC stars was 45 $M_\odot$, suggesting that stars with masses from 30 to 45 $M_\odot$ might correspond to path 3, while stars with masses 45–85 $M_\odot$ correspond to path 2.

The rare "Ofpe/WN9" stars,[6] once thought to be a transition type between "Of" stars and Wolf-Rayet stars, are only found in clusters and associations with the lowest turnoff masses, 25–35 $M_\odot$. Recently, the Ofpe/WN9 stars were implicated in the LBV phase of massive stars, after one Ofpe/WN9 star (R127) underwent an "LBV-like" outburst. However, the classical LBVs in our LMC sample, including the archetype itself, S Doradus, are found in clusters with the very highest turnoff masses, over 85 $M_\odot$ (similarly, the SMC W-R star HD 5980, which many consider to be a "true" LBV [Barbá et al. 1995], is found in a cluster with a very high turnoff mass). We conclude that the Ofpe/WN9 stars are just the lowest mass versions of W-R stars. True LBVs, on the other hand, are found only in the clusters with the highest mass turnoffs, suggesting that they are indeed stars near their Eddington limit and are a normal stage of the most massive stars.

Our study also shed light on the origin of the different W-R classes and subtypes, at least at the modest metallicity that characterizes the LMC. The WNE stars in the LMC are found in clusters with a large range of turnoff masses (from 30 to 100 $M_\odot$ or more), suggesting that these are a stage that most massive stars go through at LMC-like metallicities.

We turn now to the higher metallicity of our own Milky Way and pose the question of where LBVs and W-R stars of various types come from at a metallicity considerably higher than that of the Magellanic Clouds.

2. THE SAMPLE

Previous attempts to use Galactic OB associations and clusters to measure the progenitor masses of W-R stars have been made by Schild & Maeder (1984), Humphreys, Nichols, & Massey (1985), and Vázquez & Feinstein (1990); Smith, Meynet, & Mermilliod (1994) also discuss the issue, but primarily with an emphasis on using the data for bolometric corrections. These studies relied upon results from the literature and did not obtain new spectroscopy of the cluster stars. Our experience, even in nearby young clusters, is that many of the high-mass stars have been overlooked.[7]

In this paper, we draw upon the literature but also obtain new spectroscopy for the regions where this is required. We note that few of these regions have modern photometry. This is largely irrelevant for our purposes, as discussed further in § 2.2.2 below, but it does affect any attempts to use the distances as probes of Galactic structure.

2.1. *Selection*

For our sample, we began with the lists of W-R stars believed to be likely members of clusters and associations given by Lundström & Stenholm (1984) and Schild & Maeder (1984). We eliminated the many regions that lacked *UBV* photometry (unfortunately, this excludes many fine southern regions), were too large (NGC 2439, Vul OB2), or were too sparse (the "HD 155603 group"). This left us with 12 associations for which either we obtained new spectroscopy or adequate data existed in the recent literature. We list these regions in Table 1.

---

[5] For convenience in talking about the metallicity Z, we adopt $Z = 0.018$ for the solar neighborhood, corresponding to $\log(O/H) + 12 = 8.70$ (Esteban & Peimbert 1995). If we then simply scale Z relative to the easily measured oxygen abundance, $Z = 0.005$ for the SMC [$\log(O/H) + 12 = 8.13$] and $Z = 0.008$ for the LMC [$\log(O/H) = 8.37$] (see, e.g., Russell & Dopita 1990). Although it is well recognized that different metals will have different relative abundances, it is fortuitous that it is oxygen (along with carbon and nitrogen) that is the primary accelerator of the stellar winds at the high effective temperatures appropriate to O-type stars (Abbott 1982).

[6] The stars may be rarer at higher metallicity than at low; 10 are known in the LMC (Bohannan & Walborn 1989), while only one is known in the Milky Way (Bohannan & Crowther 1999). Six are known in M33 (Massey et al. 1996), while one is known in the higher metallicity M31 (Massey 1998a).

[7] For example, Massey & Thompson (1991) identified numerous O-type stars previously missed in Cyg OB2, including one as early as O4 III(f). Similarly, spectroscopy by Hillenbrand et al. (1993) of NGC 6611 found stars that had been previously called "O4" were in fact of "B0 V" type (NGC 6611-188) in one case and "O5 V" in another (NGC 6611-205 = HD 168076) and provided modern spectral types for dozens of others. Massey & Johnson (1993) found another O3 If (Tr 14/16-506) even in the well-studied η Carinae region and provided new spectral types for others. Table 3 of Massey et al. (1995a) gives numerous other examples of newly discovered early-type O stars in nearby Galactic regions. Spectroscopy is of course critical for assigning location of hot stars accurately in the H-R diagram, as emphasized in Paper I and elsewhere (e.g., Massey et al. 1995a, 1995b).

TABLE 1

CLUSTERS, DERIVED DISTANCES AND REDDENINGS, SIZES, AND W-R/LBV CONTENT

Cluster[a]	$(m-M)_0$	q_r	$E(B-V)$ Median	$E(B-V)$ Range	Refs.[b]	Size (pc)	W-R Stars/LBVs Catalog	Name	Type
C0757−284 (Ruprecht 44)	13.4	0.67	0.62	0.5–0.7	New	20	WR 10	HD 65865	WN4.5
C1041−597 (Collinder 228)	12.5	0.77	0.37	0.2–1.0	New	25	WR 24	HD 93131	WN7
C1043−594 (Trumpler 14/16)	12.5	0.73	0.53	0.2–0.8	1, 2	20	WR 25	HD 93162	WN7 + abs
							...	η Car	LBV
C1511−588 (Pismis 20)	12.7	0.80	1.08	1.0–1.2	New	1	WR 67	MR 55	WN6
C1715−387	12.2	0.83	1.85	1.7–1.9	New	4	WR 87	...	WN7
							WR 89	AS 223	WN7
C1722−343 (Pismis 24)	12.0	0.80	1.73	1.6–1.9	New	4	WR 93	HD 157504	WC7
C1732−334 (Trumpler 27)	12.3	0.76	1.32	1.1–2.5	New	5	WR 95	MR 74	WC9
							WR 98	HDE 318016	WN7/C7
C2004+356 (NGC 6871)	11.7	0.71	0.46	0.4–1.1	3	20	WR 133	HD 190918	WN4.5 + O9.5 Ia
C2018+385 (Berkeley 86)	11.4	0.72	0.80	0.6–0.9	3	20	WR 139	V444 Cyg	WN5 + O6
C2019+372 (Berkeley 87)	11.0	0.83	1.62	1.4–1.9	New	7	WR 142	ST 3	WC5p (WO2)
Cygnus OB2	11.2	0.80	1.82	1.2–3.4	4	25	WR 144	MR 110	WC5
							...	VI Cyg No. 12	LBV candidate
C2313+602 (Markarian 50)	12.8	0.76	0.78	0.7–1.0	New	5	WR 157	HD 219460B	WN4.5

[a] Lyngå designation, common name, or both.

[b] References for distance and reddenings (for other references, see discussion of individual associations in § 2.3): (1) Massey & Johnson 1993; (2) DeGioia-Eastwood et al. 2001; (3) Massey et al. 1995a; (4) Massey & Thompson 1991.

Two regions not listed in the table require special comment. First, we have excluded the region NGC 3603 from our study. NGC 3603 is the Milky Way's answer to R136, in that this is a young (1–2 Myr), rich region that is so highly populated that the IMF extends up to very high masses. In both cases the *Hubble Space Telescope* was needed in order to spatially resolve a single "WN + abs" star into multiple objects, and to obtain spectra of the individual components. NGC 3603 contains several stars with WN6-like features but whose individual luminosities are much higher than that of normal W-R stars of their type, and whose spectra show unmistakable evidence of hydrogen, also not in accord with their type (this can be inferred from Fig. 2 in Drissen et al. 1995, although the significance at the time was not apparent). Massey & Hunter (1998) found the same thing in R136 and realized that these WN stars were simply "super-Of" stars—core hydrogen burning objects whose very large luminosities (corresponding to masses well above the 120 $M_\odot$ limits of published evolutionary tracks) result in such strong stellar winds that their spectral appearance mimics that of W-R stars (the same conclusion is reached by de Koter, Heap, & Hubeny 1997). An excellent comparison between the NGC 3603 and R136 objects is provided by Crowther & Dessart (1998). We ignore these objects here, primarily because we do not consider them true W-R stars.

We also call attention to the cluster NGC 6231 (the nucleus of the large Sco OB1 association), which contains two W-R stars, the WN7 star HD 151932 and the WC7 + O5–O8 binary HD 155720. Although the cluster has received recent photometric attention (Perry, Hill, & Christodoulou 1991; Sung, Bessell, & Lee 1998; Baume, Vázquez, & Feinstein 1999), there is no modern *spectroscopic* study of this highly interesting region. Such a study would bolster or refute claims of large age spreads and peculiar mass functions in this cluster, as well as potentially providing additional information on the progenitor masses of Wolf-Rayet stars.

2.2. *New Data: Spectral Types and Improved Distances and Reddenings*

2.2.1. *Spectral Types: New Data and Classification*

Owing to the recent study of a number of northern hemisphere OB young clusters and OB associations (Massey, Johnson, & DeGioia-Eastwood 1995a and references therein), most of our new spectroscopy was obtained for stars in interesting southern OB associations. The majority of the new spectra were obtained on the CTIO 1.5 m telescope with the Loral 1K CCD (1200 × 800 pixels) spectrometer on 1998 March 19 (UT) with grating 47 in second order and a $CuSO_4$ blocking filter. The dispersion was 0.56 Å pixel^{-1}, and the 100 μm slit (1".8) yielded a resolution of 1.5 Å (2.5 pixels) with coverage from 4035 to 4700 Å.

Data were also obtained from Kitt Peak telescopes of the northern clusters (Berkeley 87 and Markarian 50), as well as critical data for some stars in the southern associations, admittedly at very low elevations. Most of these were obtained on the 4 m Mayall Telescope during 1998 September 11–14. The Ritchey-Chrétien spectrograph was used with the T2KB detector (2048 × 2048 pixels), with grating KP-22 used in second order and a $CuSO_4$ blocking filter. The dispersion was 0.72 Å pixel^{-1}, and the 300 μm (2".0) slit yielded a resolution of 1.8 Å (2.5 pixels), with coverage from 3750 to 5000 Å being in good focus.

A few data were also obtained on the Kitt Peak 2.1 m telescope 1998 July 19 and 21, and on 2000 March 17, using the "GoldCam" spectrometer with its Loral 3K × 1K CCD. Grating 47 was used in second order with a dispersion of 0.47 Å pixel^{-1}, and the 250 μm (3") slit provided a resolution of 1.9 Å (4 pixels). The wavelength coverage was 3800 to 4800 Å.

Thus, in all cases the wavelength range covered the important classification lines Si IV λ4089 to He II λ4686, at resolutions of 1.5–1.9 Å. Good flat-fielding was provided by exposures of an illuminated white spot. Wavelength calibration was by means of HeAr (CTIO) and HeNeAr

(KPNO) lamps. The customary IRAF optimal extraction routines were used. We usually achieved a signal-to-noise ratio (S/N) of 80 per spectral resolution element. We classified the stars based upon the criteria given by Walborn & Fitzpatrick (1990).

We list in Table 2 the brightest stars in each of these associations, including our new spectral types plus any from the literature. We have measured accurate coordinates from the STScI's Digitized Sky Survey images and include these in Table 2 to facilitate exact identification. We describe the most interesting spectra here.

2.2.1.1. Two Newly Discovered O3 Stars

The "O3" class was introduced by Walborn (1971) as an extension of the MK classes to hotter effective temperatures. At modest resolution and S/N, the spectra show no He I lines, but strong He II. The class is clearly degenerate, as higher resolution and better S/N shows He I λ4471 with equivalent widths as large as 120–250 mÅ in some stars (Kudritizki 1980; Simon et al. 1983) and less than 75 mÅ in others (e.g., Paper I). Since the O3 class represents the hottest class, all members are of high mass, and stars of type O3 III and O3 I must be of extremely high mass. Such stars are correspondingly rare, with only five possible examples in the Milky Way (the four mentioned by Walborn 1994 plus one other possible example discovered by Massey & Johnson 1993 in Trumpler 14/16).

Thus, our discovery here of two additional such stars, both in the poorly studied cluster Pismis 24 (§ 2.3.6), is of some interest. We illustrate the spectra of these two stars, Pis 24-1 and Pis 24-17, in Figure 1. In the case of HDE 319718 = Pis 24-1, we do detect He I λ4471 with an equivalent width of 85 mÅ, comparable to that seen in the most extreme of Carina stars that originally defined the class. Pis 24-1 is clearly of type O3 If*: the "f" as both N III $\lambda\lambda$4634, 4642 and He II λ4686 are seen in emission, and the asterisk signifying N IV λ4058 emission stronger than N III. Both features are luminosity indicators, thus resulting in the "I" luminosity class. Note also the strong N V $\lambda\lambda$4603, 4619 absorption, which also appears to be stronger in O3 stars of high luminosity, although one might expect that there is also a strong temperature dependence for this line, which is not seen in O4 stars except at high luminosities. The star had been previously classified as "O4(f)" by Lortet, Testor, & Niemela (1984), although in fact Vijapurkar & Drilling (1993) had suggested an "O3 III" designation.

In the case of Pis 24-17, we do not detect He I. We would argue that its luminosity class is intermediate between "III" and "I": on the one hand, He II λ4686 is strongly in absorption while N III is in emission, suggesting an O3 III(f*) classification, given that the N IV emission is comparable in strength to that of N III. However, there is incredibly strong N V absorption, which would argue either for higher luminosity (or higher effective temperature?). Rather than attempt to introduce a II(f*) into the nomenclature, we classify the star as O3 III(f*). We are indebted to N. Walborn for his insightful comments on this spectrum. This star was labeled "N35B" by Lortet et al. (1984) and classified as O4–O5 V. Doubtless the strong nebular He I λ4471 emission disguised the O3 nature of this and Pis 24-1 on their photographic spectra.

2.2.1.2. Other Early O-Type Supergiants

We show in Figure 2 a few of our other early O-type supergiants. The spectra here can be compared with those illustrated in Walborn & Fitzpatrick (1990). These spectra, and the new types listed in Table 2, emphasize the need for modern spectroscopic studies of early-type stars even within modest distances of the Sun.

2.2.2. *Reddenings and Distances*

In order to locate the stars in the H-R diagram and assign masses, we need to know their luminosities; for this, we need to know their distances and reddenings. We have photometry (from the literature) and good spectral types (mostly new) for only the brightest dozen or so stars in each cluster (e.g., Table 2), with the exception of the clusters previously studied in order to determine their IMF. Main-sequence fitting is of little use when dealing with stars this hot, as color information (even in the absence of reddening) provides little information about effective temperature. Instead, we derive distances and reddenings through the spectral types, adopting the absolute magnitude calibration discussed in Paper I, as well as the same intrinsic color calibration.

For each star with a spectral type in Table 2, we computed the reddening and true distance modulus and then eliminated any obvious outliers. Discrepant distances canbe due either to misclassification by a luminosity class (relatively easy for the early B stars) or to nonmembership;

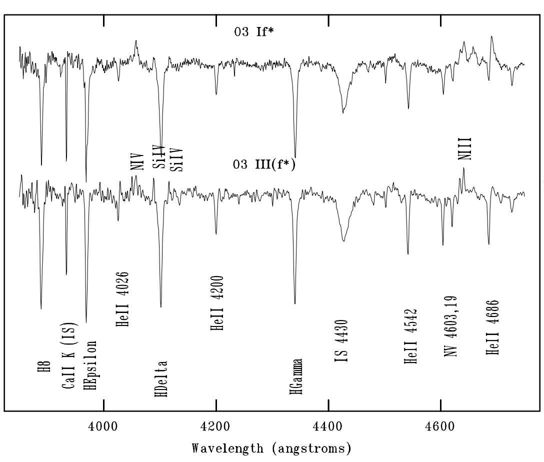

FIG. 1.—Two O3 stars in the cluster Pis 24. We classify the upper spectrum (Pis 24-1) as O3 If*, and that of the lower spectrum (Pis 24-1B) as O3 III(f*).

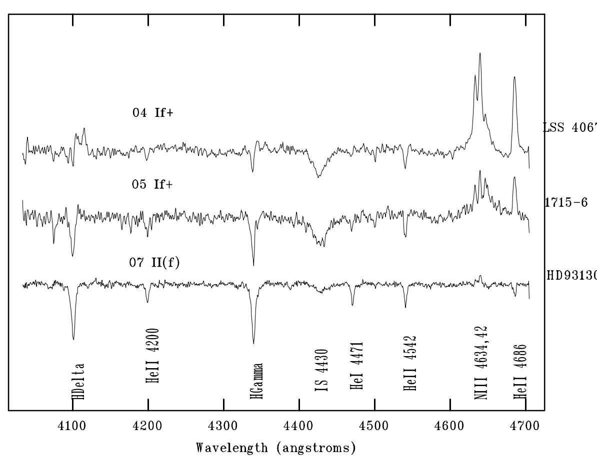

FIG. 2.—Early O-type supergiants in C1715-387 (LSS 4067 and No. 6), and in Cr 228 (HD 93130).

TABLE 2

CATALOG OF THE BRIGHTEST STARS IN OUR SAMPLE

Star	α[a] (J2000.0)	δ[a] (J2000.0)	Literature Photometry[b] V	B−V	U−B	Spectral Type and/or Comments[c]
Ruprecht 44:						
LSS 909	07 59 22.16[d]	−28 54 23.8[d]	10.07	0.30	−0.86	New: B1 V, nonmember (MF74: O8:e; RF83: B1 V)
LSS 902 = Ru 44-185	07 58 48.49[d]	−28 23 23.5[d]	10.62	0.32	−0.66	RF83: B0 V
LSS 916 = Ru 44-187	07 59 46.25[d]	−28 44 03.2[d]	10.93	0.29	−0.60	WR 10 = HD 65865; WN5
LSS 891 = Ru 44-183	07 57 58.55[d]	−28 35 29.4[d]	10.93	0.29	−0.69	New: O8 III(f) (FM76: O9.5; RF83: O8 V)
LSS 885	07 57 24.9[d]	−28 42 07[d]	10.98	0.34	−0.62	RF83: B1 V
LSS 884	07 57 20.79[d]	−28 37 58.3[d]	11.16	0.28	−0.69	New: B1 V (RF83: B2 Ve)
LSS 897 = Ru 44-184	07 58 42.94	−28 26 20.3	11.18	0.29	−0.66	RF83: B0 V (FM76: B0 V)
LSS 907 = Ru 44-186	07 59 08.64	−28 31 08.0	11.18	0.36	−0.61	New: B0 V (RF83: O9 V)
LSS 899 = Ru 44-182	07 58 51.84[d]	−28 45 04.2[d]	11.30	0.27	−0.67	New: O9 III (MF76: O8; RF83: B0 V)
LSS 898 = Ru 44-94	07 58 45.79	−28 32 46.6	11.31	0.50	−0.63	New: Be (FM76: Oe)
LSS 920	08 00 03.26[d]	−28 50 25.7[d]	11.38	0.24	−0.68	New: O9.5 V (RF83: O8 V)
LSS 916 SF	07 59 49.11	−28 44 39.6	11.60	0.26	−0.68	South-following companion of WR 10
LSS 901 = Ru 44-33	07 58 56.89[d]	−28 33 30.2[d]	11.63	0.37	−0.57	New: B2 III: (FM76: B0 III; RF83: B1 V)
LSS 908 = Ru 44-128	07 59 12.06	−28 34 05.0	11.64	0.34	−0.62	New: B0.2 V (FM76: B1 V; RF83: O9 V)
Ru 44-27	07 58 55.53	−28 35 24.8	11.93	0.35	−0.57	New: B0.5 V
LSS 906 = Ru 44-148	07 59 05.98	−28 36 50.9	12.15	0.39	−0.55	New: B1 V (FM76: O9:; RF83: B1 V)
LSS 903 = Ru 44-41	07 58 58.10	−28 38 35.9	12.20	0.35	−0.52	RF83: B2 V
Ru 44-93	07 58 45.79	−28 33 01.2	12.51	0.38	−0.35	MF74: B3:
Ru 44-19	07 58 52.06	−28 35 06.0	12.55	0.34	−0.48	
Ru 44-2	07 58 52.18	−28 36 04.9	12.63	0.39	−0.40	
Ru 44-3	07 58 48.96	−28 35 47.7	12.65	0.41	−0.42	
Ru 44-24	07 58 53.60	−28 35 03.2	12.79	0.37	−0.45	
Ru 44-59	07 58 45.22	−28 36 51.4	13.18	0.38	−0.44	
Ru 44-112	07 58 56.79	−28 32 50.4	13.56	0.40	−0.34	
Ru 44-102	07 58 49.09	−28 31 28.6	13.57	0.41	−0.43	
Ru 44-114	07 58 54.77	−28 31 29.6	13.72	0.38	−0.41	
Ru 44-60	07 58 45.20	−28 36 47.7	13.72	0.40	−0.38	
Ru 44-40	07 59 01.82	−28 37 52.5	13.81	0.39	−0.36	
Ru 44-14	07 58 51.42	−28 33 30.1	13.83	0.44	−0.29	
Ru 44-113	07 58 54.03	−28 33 08.7	14.06	0.38	−0.29	
Ru 44-51	07 58 54.52	−28 36 14.8	14.31	0.36	−0.40	
Ru 44-6	07 58 42.95	−28 35 02.4	14.80	0.52	−0.16	
Ru 44-88	07 58 41.08	−28 32 43.0	14.82	0.49	−0.22	
Ru 44-84	07 58 38.15	−28 34 22.1	14.97	0.64	−0.10	
Collinder 228:						
HD 93206 = Cr 228-33	10 44 22.91[d]	−59 59 35.9[d]	6.28	0.14	−0.80	New: O9.5 I [W73: O9.7 Ib:(n); LM81: O9.5 Ib: + O9.5 III:]
HD 93131 = Cr 228-3	10 43 52.26[d]	−60 07 04.0[d]	6.48	−0.02	−0.88	WR 24; WN7
HD 93130 = Cr 228-1	10 44 00.35[d]	−59 52 27.9[d]	8.04	0.27	−0.71	New: O7 II(f) [W73: O6 III(f); LM81: O6 III(f)]
HD 93222 = Cr 228-6	10 44 36.24[d]	−60 05 29.0[d]	8.08	0.08	−0.84	New: O8 III((f)) [W73: O7 III((f)); LM81: O7 III((f))]
HD 93028 = Cr 228-27	10 43 15.34[d]	−60 12 04.2[d]	8.36	−0.06	−0.89	New: O8.5 III (W73: O9 V; LM81: O8.5 V)
HD 93632 = Cr 228-92	10 47 12.49[d]	−60 05 49.8[d]	8.39	0.29	−0.73	New: O5 III(f) [LM81: O5 III(f); W73: O5 III(f)]
HD 93146 = Cr 228-65	10 44 00.02	−60 05 11.3	8.41	0.00	−0.92	W73: O6.5 V((f)) (LM81: O6 V)
HD 93191 = Cr 228-2	10 44 27.50[d]	−59 53 05.9[d]	8.48	−0.02	−0.18	LM81: Nonmember (B9.5 V)
HDE 305523 = Cr 228-32	10 44 29.42[d]	−59 57 18.4[d]	8.49	0.18	−0.76	LM81: O8.5 II–III
HDE 305520 = Cr 228-4	10 44 05.83[d]	−59 59 41.7[d]	8.68	0.17	−0.69	LM81: B1 Ib
HD 93027 = Cr 228-14	10 43 17.96[d]	−60 08 03.2[d]	8.72	0.00	−0.86	New: O9 V (W73: O9.5 V; LM81: O9.5 IV)
Cr 228-67	10 44 00.49	−60 06 01.2	8.77	0.00	−0.82	New: O9 V (LM81: O9 V)
Cr 228-88	10 45 52.00	−60 11 33.2	8.79	0.14	0.17	
HDE 305438 = Cr 228-24	10 42 43.78[d]	−59 54 16.5[d]	8.80	−0.01	−0.89	New: O8 V((f)) (LM81: O7.5 V)
HDE 305536 = Cr 228-5	10 44 11.17	−60 03 21.5	8.94	0.05	−0.82	New: O9.5 V (LM81: O8.5 V)
HD 93056 = Cr 228-13	10 43 27.49	−60 05 54.7	8.97	−0.06	−0.78	LM81: B1 Vb:
HDE 305437 = Cr 228-23	10 42 45.18[d]	−59 52 19.7[d]	9.06	0.02	−0.80	New: B0.5 V (LM81: B0.5 V)
HD 93501 = Cr 228-96	10 46 22.04[d]	−60 01 19.0[d]	9.08	0.10	−0.67	LM81: B1.5 III: SB2?
HDE 305524 = Cr 228-7	10 44 45.2[d]	−59 54 41.5[d]	9.28	0.30	−0.72	New: O7 V((f)) (LM81: O6 Vn)
Cr 228-21	10 43 57.59	−60 05 28.0	9.31	0.02	−0.86	New: O8.5 V (LM81: O7.5 Vn)
HDE 305535 = Cr 228-25	10 42 54.68[d]	−59 58 19.7[d]	9.39	0.04	−0.44	LM81: B2.5 V
HD 93647 = Cr 228-90	10 47 20.50[d]	−60 12 57.0[d]	9.44	0.11	0.15	LM81: Nonmember (A2: V)
Cr 228-12	10 44 36.88	−59 54 24.9	9.47	0.82	−0.29	LM81: B2.5 Ia:
HD 93576 = Cr 228-93	10 46 53.84[d]	−60 04 41.9[d]	9.57	0.25	−0.69	LM81: O9 V
HDE 305534 = Cr 228-11	10 44 47.51[d]	−59 57 58.9[d]	9.67	0.13	−0.75	LM81: B0.5 V: + B1 V:
HDE 305522 = Cr 228-8	10 44 19.94[d]	−60 00 05.8[d]	9.69	0.06	−0.76	LM81: B0.5 V: + companion?

TABLE 2—*Continued*

Star	α[a] (J2000.0)	δ[a] (J2000.0)	Literature Photometry[b] V	$B-V$	$U-B$	Spectral Type and/or Comments[c]
HDE 305518 = Cr 228-22	10 43 44.00[d]	−59 48 17.9[d]	9.71	0.38	−0.59	LM81: O9.5 IV
HDE 305543 = Cr 228-28	10 43 10.07[d]	−60 02 11.7	9.74	0.05	−0.77	New: B1 III (LM81: B1 V + B1 V)
HD 93097 = Cr 228-69..............	10 43 46.95	−60 05 50.5	9.76	−0.02	−0.81	LM81: B0 V
Cr 228-66	10 43 59.4:	−60 05 14:	9.79	0.07	−0.79	LM81: O9.5 V
HDE 305521 = Cr 228-16	10 43 49.50	−59 57 22.4	9.81	0.06	−0.69	LM81: B0.5 V
HD 305519 = Cr 228-57	10 44 11.21	−59 55 30.9	9.86	0.09	0.08	LM81: Nonmember (A2 V)
HDE 305516 = Cr 228-31	10 43 15.78	−59 51 05.3	9.87	0.06	−0.77	New: B0.5 V (LM81: B0.5 V:)
HDE 305539 = Cr 228-94	10 46 33.07[d]	−60 04 12.6[d]	9.90	0.27	−0.74	New: O8.5 V (LM81: O7 V; W82: O7p)
Cr 228-39	10 44 54.80	−59 56 02.1	9.92	0.32	−0.76	New: O8.5 V((f)) (LM81: O8 V)
HDE 305525 = Cr 228-98	10 46 05.70[d]	−59 50 49.3[d]	10.00	0.68	−0.42	LM81: O6 V
HDE 305540 = Cr 228-91	10 47 11.44[d]	−60 11 47.1[d]	10.05	0.09	−0.05	LM81: Nonmember (A0 V)
Cr 228-68	10 44 00.2:	−60 06 10:	10.16	0.05	−0.73	LM81: B1 V
Cr 228-35	10 44 37.39	−60 00 59.6	10.18	−0.01	−0.16	LM81: B9.5 V
HDE 305532 = Cr 228-38	10 45 34.06	−59 57 26.7[d]	10.20	0.34	−0.74	W82: O6 V((f)) (LM81: O5 V)
Cr 228-29	10 42 36.44	−60 02 34.5	10.21	0.07	−0.36	LM81: Nonmember (B9.5 Vp?)
Cr 228-36	10 44 36.99	−60 01 11.4	10.23	0.10	−0.62	LM81: B0.5: V + B0.5: V:
HDE 305528 = Cr 228-80	10 45 16.71[d]	−59 54 45.9[d]	10.28	0.13	−0.49	LM81: B2 V
HDE 305533 = Cr 228-47	10 45 13.46	−59 57 54.0	10.32	0.13	−0.51	LM81: B0.5: Vnn + shell
HDE 305515 = Cr 228-44	10 43 04.23[d]	−59 51 39.2[d]	10.35	0.09	−0.59	LM81: B1.5 V
Cr 228-97	10 46 22.54	−59 53 20.7	10.36	0.51	−0.64	W82: O5 V (LM81: O5 V)
Cr 228-43	10 43 45.14	−59 53 25.2	10.40	0.22	−0.66	LM81: B2 V
Cr 228-20	10 44 15.23	−60 07 53.0	10.41	0.67	−0.22	T88: B2 V
Cr 228-89	10 47 13.28	−60 13 34.3	10.43	−0.03	−0.69	LM81: B2 V
Cr 228-42[e]	...	...	10.48	0.66	0.20	
Cr 228-19	10 44 15.96	−60 09 04.2	10.52	0.09	−0.70	LM81: B1: V: SB2
HDE 305538 = Cr 228-82	10 45 46.46[d]	−60 05 13.7[d]	10.53	0.25	−0.53	LM81: B0 V
Cr 228-87	10 45 32.42	−60 06 17.6	10.55	0.16	−0.12	LM81: Nonmember (B9 V)
Cr 228-40	10 44 32.94	−59 52 52.8	10.62	1.14	0.86	
Cr 228-26	10 43 14.98	−60 07 47.7	10.63	0.21	−0.03	LM81: Nonmember (A0 V)
HDE 305537 = Cr 228-83	10 45 44.55	−60 04 23.7	10.74	0.09	−0.60	LM81: Nonmember (B9.5 V)
Cr 228-46	10 44 56.71	−60 07 56.3	10.74	0.16	0.15	LM81: Nonmember (A1 V)
Cr 228-30	10 42 36.22	−59 59 25.8	10.80	0.05	−0.69	LM81: B1.5 V
Cr 228-37	10 45 06.57	−60 00 48.5	10.81	0.21	−0.63	LM81: B2 V
Cr 228-81	10 45 53.58	−60 05 37.2	10.89	0.20	−0.62	LM81: B0.5 V
Cr 228-53	10 43 51.39	−59 57 20.0	10.94	0.10	−0.65	
Cr 228-95	10 46 25.47	−60 08 44.5	10.98	0.02	−0.63	LM81: B0 V
Cr 228-48	10 43 48.95	−60 09 00.9	11.00	−0.03	−0.62	LM81: B1.5 V
Cr 228-84	10 45 38.81	−60 04 26.3	11.05	0.25	−0.44	
Cr 228-86	10 45 45.15	−60 06 31.4	11.06	0.98	1.28	
Cr 228-41	10 44 30.11	−59 52 14.0	11.06	0.21	−0.63	
Cr 228-18	10 44 50.59	−59 55 44.9	11.07	0.25	−0.70	
Cr 228-75	10 43 50.04	−60 01 54.1	11.15	0.32	0.19	
Cr 228-85	10 45 34.22	−60 04 31.7	11.20	0.78	0.50	
Cr 228-49	10 42 46.22	−60 00 57.5	11.20	0.01	−0.36	
Cr 228-78	10 43 31.62	−60 03 16.2	11.44	0.18	−0.36	
Cr 228-77	10 43 48.87	−60 00 36.8	11.57	0.20	−0.58	
Cr 228-74	10 43 46.88	−60 08 26.4	11.66	0.18	−0.43	
Cr 228-61	10 44 01.0:	−59 52 40:	11.70	0.22	−0.59	
Cr 228-55	10 43 39.85	−59 55 16.2	11.71	0.31	0.14	
Cr 228-51	10 44 14.54	−60 01 27.3	11.88	0.10	−0.61	
Trumpler 14/16: See Massey & Johnson 1993						
Pismis 20:						
HD 134959 = Pis 20-1	15 15 24.07	−59 04 29.2	8.20	0.93	−0.07	B2.5 Ia
Pis 20-2	15 15 23.82	−59 04 17.9	10.45	0.71:	−0.17	O8.5 I
Pis 20-3	15 15 22.41	−59 04 17.4	10.75	0.90	−0.14	B0 I
Pis 20-4	15 15 22.41	−59 04 30.3	11.37	0.87	−0.11	B0.2 III
Pis 20-5	15 15 23.56	−59 03 59.2	11.96	0.89	−0.10	B0 I–III
Pis 20-6	15 15 19.56	−59 03 24.1	11.91	1.07	−0.09	Early B V
LSS 3327 = Pis 20-7................	15 15 17.26	−59 04 48.7	11.29	0.83	−0.17	B0 I–III
WR 67 = HD 134877 = Pis 20-8...	15 15 32.63	−59 02 30.6	11.94	0.65	−0.13	WN6
C1715−387:						
LSS 4065 = C1715−387 No. 1.....	17 19 00.50	−38 48 52.5	11.02	1.54	0.41	New: WN7 (HM77: WN8 + OB; WF00: WN8-A)
LSS 4067 = C1715−387 No. 2.....	17 19 05.51	−38 48 50.5	11.16	1.54	0.37	New: O4 If+ (HM77: O4f)
C1715−387 No. 6	17 19 05.96	−38 46 46.1	11.64	1.54	0.35	New: O5 If+ (HM77: O5f)

TABLE 2—*Continued*

Star	α[a] (J2000.0)	δ[a] (J2000.0)	Literature Photometry[b] V	$B-V$	$U-B$	Spectral Type and/or Comments[c]
LSS 4064 = C1715−387 No. 3...	17 18 52.82	−38 50 04.7	12.00	1.70	0.57	WN7 (HM77: WN8 + OB)
C1715−387 No. 8	17 19 04.38	−38 49 05.8	12.52	1.52	0.37	New: O5 V (HM77: O8)
C1715−387 No. 12	17 18 42.77	−38 49 51.3	12.57	1.52	0.37	New: O6 If
C1715−387 No. 13	17 18 47.59	−38 49 58.8	12.77	1.50	0.38	New: O7 V((f)) (HM77: O8)
C1715−387 No. 9	17 19 05.70	−38 49 03.2	12.99	1.59	0.41	
C1715−387 No. 16	17 18 53.32	−38 51 14.2	13.20	1.78	0.60	
C1715−387 No. 18	17 19 00.73	−38 49 24.2	13.41	1.46	0.30	
C1715−387 No. 20	17 18 44.85	−38 50 01.3	13.45	1.35	0.17	New: O9.5 V
C1715−387 No. 10	17 19 01.0:	−38 49 03:	13.64	1.52	0.30	
C1715−387 No. 19	17 19 01.63	−38 49 11.5	14.15	1.58	0.39	
C1715−387 No. 23	17 19 04.69	−38 49 51.0	15.03	1.50	0.39	
C1715−387 No. 24	17 19 05.57	−38 49 27.8	15.64	1.21	0.30	
Pismis 24:						
HDE 319718 = Pis 24-1	17 24 43.41	−34 11 56.5	10.43	1.45	0.40	New: O3 If* [C71: O7; LTN84: O4(f)]
HD 157504 = WR 93	17 25 08.79	−34 11 12.1	(11.46)	(1.15:)	...	WC7 (+abs?)
Pis 24-17	17 24 44.7:	−34 12 02:	11.84	1.49	...	New: O3 III(f*) (LTN84: O4–O5 V; see text for ID)
Pis 24-2	17 24 43.20	−34 12 43.5	11.95	1.41	0.32	New: O5.5 V((f))
Pis 24-15	17 24 28.86	−34 14 50.3	12.32	1.27	0.14::	New: O8 V
Pis 24-13	17 24 45.68	−34 09 39.2	12.73	1.48	0.11	New: O6.5 V((f))
Pis 24-3	17 24 42.21	−34 13 21.0	12.75	1.41	0.24	New: O8 V
Pis 24-8	17 24 38.81	−34 14 58.2	12.98	1.44	0.48	
Pis 24-10	17 24 35.94	−34 13 59.9	13.02	1.40	0.40	New: O9 V
Pis 24-16	17 24 44.3:	−34 12 00:	13.02	1.60	...	New: O7.5 V (see text for ID)
Pis 24-7	17 24 47.81	−34 15 16.5	13.46	1.68	0.58	
Pis 24-12	17 24 42.22	−34 11 41.1	13.88	1.47	0.38	New: B1 V
Pis 24-4	17 24 40.39	−34 12 05.9	13.93	1.43	0.53	
Pis 24-18	17 24 43.2:	−34 11 42:	13.97	1.48	...	New: B0.5 V: (see text for ID)
Pis 24-9	17 24 39.29	−34 15 26.4	14.26	1.40	0.40	
Pis 24-11	17 24 34.68	−34 13 17.1	14.53	1.57	0.30::	
Pis 24-19	17 24 43.5:	−34 11 41:	14.43	1.39	...	New: B1 V (see text for ID)
Trumpler 27:						
Tr 27-1	17 36 10.07	−33 29 40.5	8.79	3.12	3.32	New: M0 Ia (MFJ77: M0 Ia)
Tr 27-1a	17 36 10.1:	−33 29 36	12.70	1.55	0.28	
LSS 4253 = Tr 27-2	17 36 10.74	−33 28 48.1	10.55	1.28	0.18	New: B0 Ia (MFJ77: O9 Ia)
Tr 27-3	17 36 12.94	−33 28 51.6	13.16	1.17	0.19	
Tr 27-4	17 36 13.21	−33 30 05.4	11.93	0.59	0.16	
Tr 27-5	17 36 10.42	−33 30 02.3	12.16	1.23	0.08	New: B2.5 Ib
Tr 27-8	17 36 09.69	−33 30 54.7	11.88	1.66	0.56	
Tr 27-10	17 36 15.55	−33 31 28.8	12.12	1.64	0.76	
Tr 27-11	17 36 18.92	−33 31 24.3	12.34	0.96	0.03	
Tr 27-12	17 36 22.12	−33 31 10.9	12.05	1.57	0.48	
LSS 4264 = Tr 27-13	17 36 25.20	−33 31 08.5	11.78	0.96	−0.01	
LSS 4262 = Tr 27-14	17 36 23.31	−33 31 45.4	11.12	1.18	0.15	MFJ77: B0 Ib
LSS 4263 = Tr 27-16	17 36 24.31	−33 33 10.0	10.74	1.09	−0.01	New: B0.5 Ia (MFJ77: O9.5 II:)
Tr 27-19	17 36 32.17	−33 31 51.5	12.74	1.03	0.06	
Tr 27-20	17 36 28.72	−33 31 32.9	13.63	0.81	−0.16	
Tr 27-21	17 36 35.31	−33 30 13.0	12.59	0.90	−0.06	
LSS 4266 = Tr 27-23	17 36 27.36	−33 29 35.9	10.11	1.43	0.37	New: B0.7 Ia (MFJ77: B0.5 Ib)
Tr 27-25	17 36 37.60	−33 27 21.8	11.42	1.41	0.34	
Tr 27-27	17 36 29.91	−33 26 34.2	13.31	2.16	0.74	New: O8 III((f))
Tr 27-28 = WR 95	17 36 19.86	−33 26 12.2	13.38	1.77	0.86	WC9 (MFJ77: WN5)
Tr 27-30	17 36 05.55	−33 27 50.8	13.79	1.48	0.65	
Tr 27-32	17 36 35.23	−33 34 32.8	12.98	1.07	−0.18	New: B1.5: V:
Tr 27-34	17 36 45.14	−33 31 55.0	12.94	1.03	0.03	MFJ77: B1: V:
Tr 27-36	17 36 36.11	−33 30 58.6	13.18	1.08	0.16	
Tr 27-37	17 36 37.12	−33 31 00.9	13.99	1.13	0.30	
Tr 27-40	17 36 40.12	−33 28 41.7	13.88	0.79	0.14	
Tr 27-41	17 36 40.56	−33 28 03.3	14.05	0.87	0.18	
Tr 27-42	17 36 08.19	−33 28 55.5	14.22	1.23	0.16	New: B3 V
Tr 27-43	17 36 14.43	−33 29 16.8	10.48	1.99	1.06	New: B8 I (MFJ77: B9 Ia)
Tr 27-44	17 36 34.54	−33 30 16.2	12.11	0.92	−0.10	New: Nonmember? B1.5 Ia (MFJ77: B1: II::)
Tr 27-46	17 36 12.81	−33 29 18.9	8.79	1.60	0.65	New: B8 I (MFJ77: B9 Ia)
Tr 27-46a	17 36 13.6:	−33 29 09:	11.54	1.73	0.77	
Tr 27-46b	17 36 12.8:	−33 29 12:	12.98	1.34	0.30	

TABLE 2—*Continued*

Star	α[a] (J2000.0)	δ[a] (J2000.0)	Literature Photometry[b] V	$B-V$	$U-B$	Spectral Type and/or Comments[c]
Tr 27-46c	17 36 13.1:	−33 29 05:	13.28	1.45	0.33	
Tr 27-47	17 36 14.25	−33 29 36.1	14.34	1.86	0.95	
Tr 27-49	17 36 17.33	−33 30 02.0	14.32	1.54	0.69	
Tr 27-52	17 36 21.74	−33 28 34.5	14.14	1.24	0.27	
Tr 27-53	17 36 27.46	−33 29 15.8	14.10	1.64	0.50	
Tr 27-55	17 36 31.87	−33 28 36.4	14.43	1.06	0.13	
Tr 27-61	17 36 29.50	−33 30 46.0	13.90	1.09	0.24	
Tr 27-62	17 36 26.38	−33 30 36.3	14.28	0.82	0.11	
Tr 27-64	17 36 23.05	−33 34 37.3	14.95	1.36	0.42	
Tr 27-68	17 36 10.73	−33 31 52.2	14.33	0.95	0.18	
Tr 27-69	17 36 03.51	−33 29 54.1	14.23	0.96	0.20	
Tr 27-102	17 35 56.31	−33 25 56.2	8.39	1.94	1.71	New: G0 I (MFJ77: G0 Ia)
Tr 27-103	17 35 32.74	−33 27 41.2	10.69	0.99	−0.07	MFJ77: B1 II
LSS 4271 = Tr 27-104	17 36 39.75	−33 21 16.6	10.69	0.79	−0.29	New: O8.5 III (MFJ77: O9 III)
HDE 318016 = Tr 27-105	17 37 13.72	−33 27 56.1	11.85	1.37	0.49	WR 98; WC7/WN6
LSS 4259 = Tr 27-106	17 36 17.64	−33 36 36.3	11.43	1.02	0.07	MFJ77: B2 III
LSS 4257 = Tr 27-107	17 36 16.63	−33 38 10.2	11.46	0.94	−0.16	New: Nonmember? B0.5 Ia (MFJ77: B0 V)
NGC 6871: See Massey et al. 1995a						
Berkeley 86: See Massey et al. 1995a						
Berkeley 87:						
HDE 229059 = Berk 87-3	20 21 15.37	37 24 31.3	8.71	1.52	0.40	New: B1 Ia (TF82: B2 Ia)
Berk 87-4	20 21 19.25	37 23 24.3	10.92	1.26	0.22	New: B0.2 III:
Berk 87-5	20 21 18.66	37 22 31.0	14.65	1.35	0.34	
Berk 87-7	20 21 23.14	37 20 06.2	13.02	1.11	0.28	
Berk 87-9	20 21 24.88	37 22 48.0	12.09	1.33	0.34	New: B0.5 V
Berk 87-13	20 21 31.56	37 20 41.2	11.32	1.09	0.12	New: B0.5 III:
Berk 87-14	20 21 33.56	37 25 23.0	14.12	1.33	0.82	
V439 Cyg = Berk 87-15	20 21 33.60	37 24 51.6	11.84	1.54	0.37	New: B[e]
Berk 87-16	20 21 33.49	37 24 19.4	13.39	1.33	0.55	New: B2 V
Berk 87-18	20 21 35.27	37 29 12.2	12.84	1.63	0.66	New: B1 V
Berk 87-22	20 21 36.80	37 24 32.9	13.96	1.46	0.55	
Berk 87-24	20 21 38.03	37 25 17.1	11.48	1.34	0.37	New: B1 Ib
Berk 87-25	20 21 38.67	37 25 15.5	10.46	1.29	0.19	New: O8.5 III (TF82: O9 V)
Berk 87-26	20 21 39.70	37 25 05.4	11.83	1.42	0.38	New: B0.5 I
Berk 87-27	20 21 39.76	37 22 39.4	13.51	1.35	0.53	
ST 3 = Berk 87-29	20 21 44.38	37 22 30.3	12.96	1.43	−0.29	WR 142; WC4
Berk 87-31	20 21 45.90	37 22 25.7	12.32	1.40	0.38	New: B1 V
Berk 87-32	20 21 47.35	37 26 31.8	11.57	1.34	0.31	New: B0.5 III
Berk 87-34	20 21 51.04	37 26 05.3	13.32	1.53	0.63	
Berk 87-35	20 21 54.38	37 23 32.2	13.85	1.43	0.68	
Berk 87-38	20 21 59.97	37 26 23.7	12.44	1.58	0.52	New: B2 III:
Cygnus OB2: See Massey & Thompson 1991						
Markarian 50:						
HD 219460A	23 15 12.5:	60 27 01:	10.7:	0.52	...	C75: B0 III (photometry from C75, corrected for companion)
HD 219460B	...	...	10.9:	0.52	...	New: WN4.5 (photometry from C75, corrected for companion)
Ma 50-23	23 15 16.68	60 26 07.0	10.68	0.46	−0.41	New: B1 III (C75: B0.5 III)
Ma 50-31	23 15 11.97	60 26 46.7	11.21	0.64	−0.27	New: B0.5 II (C75: B1 III)
Ma 50-30A	23 15 13.0:	60 26 21:	11.90	0.58	−0.25	New: B1.5 V (C75: B2 V)
Ma 50-1	23 14 59.86	60 27 15.3	12.33	0.45	−0.35	New: B1.5 V (C75: B1.5 V)
Ma 50-30	23 15 14.37	60 26 18.4	12.42	0.49	−0.36	New: B2 V (C75: B2 V)
Ma 50-31A	23 15 13.7:	60 27 01:	12.93	0.76	0.03	New: B3 V
Ma 50-25	23 15 16.48	60 26 21.8	13.79	0.55	−0.06	New: B3 V
Ma 50-26	23 15 13.64	60 26 06.4	13.90	0.66	0.06	New: B5 V
Ma 50-24	23 15 18.07	60 26 05.9	14.04	0.60	0.11	New: B8 V

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

[a] Coordinates measured from Digitized Sky Survey images.

[b] The references for photometry are as follows: Ru 44, Turner 1981; Cr 228, Feinstein et al. 1976; Pis 20, Moffat & Vogt 1973; C1715−387, Havlen & Moffat 1977; Pis 24, Moffat & Vogt 1973; Tr 27, Moffat et al. 1977; Berk 87, Turner & Forbes 1982; Ma 50, Turner et al. 1983.

[c] The reference for spectral types are (C71) Crampton 1971; (C75) Crampton 1975; (MF74) Moffat & FitzGerald 1974; (FM76) FitzGerald & Moffat 1976; (HM77) Havlen & Moffat 1977; (LM81) Levato & Malaroda 1981; (LTN84) Lortet et al. 1984; (MFJ77) Moffat et al. 1977; (RF83) Reed & FitzGerald 1983; (T88) quoted in Tapia et al. 1988; (TF82) Turner & Forbes 1982; (W73) Walborn 1973a; (W82) Walborn 1982; (WF00) Walborn & Fitzpatrick 2000.

[d] Coordinates from SIMBAD.

[e] Appears to be missing from the finding chart of Feinstein et al. 1976.

multiplicity must also play an occasional role. The results are given in Table 1, along with the other data on the clusters. We have also included an estimate of the size of the region. In general, the determination of the distance moduli is good to 0.1 mag.[8]

2.3. *Discussion of Individual Clusters*

2.3.1. *Ruprecht 44 (C0757−284)*

The Ru 44 cluster has been described by Moffat & FitzGerald (1974), FitzGerald & Moffat (1976), Havlen (1976), and Turner (1981; see also McCarthy & Miller 1974). The cluster is a condensation in the Pup OB2 association. The WN4.5 star WR 10 (HD 65865 = MR 11) is listed by Moffat & FitzGerald as a member, although it lies well outside the central part of the cluster (the "core" as shown in Fig. 1 of Moffat & FitzGerald 1974 has a radius of 6.′4; the W-R star lies 14′ to the southeast of its center). Distance estimates have ranged from the large values of Moffat & FitzGerald (1974) and FitzGerald & Moffat (1976), who proposed distance moduli of 14.1–14.2 mag (6.6–6.8 kpc), to the smaller value of 13.2 mag (4.3 kpc) found by Havlen (1976). The most recent and complete study is that of Turner (1981), who finds a distance modulus of 13.3 mag (4.7 kpc) from main-sequence fitting, in accord with the Hβ value of Havlen.

Many of the existing spectral types in the cluster are listed by Moffat & FitzGerald (1974) and Turner (1981) as uncertain, and we obtained new spectral information for eight stars. We find that the stars described as O type are generally no earlier than B type; for instance, the star LSS 909, described as "O6:e" by Moffat & FitzGerald, and revised to "O8" by Turner, is actually a B1 V according to our CCD spectroscopy and is likely a foreground object (it was included as one of the outlying possible members by Turner). Similarly, the star LSS 899 (Ru 44-182) was classified by Moffat & FitzGerald (1974) as "O8 V" but subsequently reclassified as B0 V by Reed & FitzGerald (1983). On the other hand, the star LSS 891 (Ru 44-183) was called "O9.5" by FitzGerald & Moffat (1976) and is actually an O8 III(f) according to our spectroscopy, similar to the O8 V classification by Reed & FitzGerald. Our derived distance modulus of 13.35 mag is in excellent accord with that found by Turner (1981).

2.3.2. *Collinder 228 (C1041−597)*

Cr 228 is just south of the η Carinae clusters Tr 14 and Tr 16, and Cr 232 (see Fig. 1 in Massey & Johnson 1993). An excellent spectroscopic study of this region was conducted by Walborn (1973a, 1982). In constructing our list of members, we began with the *UBV* photometry of Feinstein, Marraco, & Forte (1976; the photometry of HD 93146 comes from Turner & Moffat 1980). Spectral types are from Walborn (1973a, 1982), as well as Levato & Malaroda (1981), with a few additional types from Tapia et al. (1988) based upon unspecified sources. To this we add our own 16 new spectral types, mostly of stars with previous spectroscopy; the agreement between different sources is generally very good. We eliminate stars thought to be nonmembers based on spectra or color, as indicated by Tapia et al. We also ignore the plethora of stars with late B or early A dwarf spectral types in determining the distance modulus or constructing the H-R diagram. The resulting true distance modulus is 12.45 mag (3.1 kpc) and the average color excess $E(B-V) = 0.37$. [Our *apparent* distance modulus, 13.6 mag, is identical to that found by Tapia et al., but the *true* distance modulus is somewhat greater since they derive a higher average reddening for Cr 228 based upon calculating $E(B-V)$ from their measured $E(V-K)$ values.] Our distance modulus would place the cluster at essentially the same distance as the rest of the η Car complex (see Massey & Johnson 1993). A few of the stars have luminosity classes or reddenings inconsistent with the adopted distance, but the corrections are minor and probably all of these stars with spectral types are members. The W-R member is WR 24, of type WN7.

2.3.3. *Trumpler 14/16*

The LBV star η Car is part of the Tr 14/16 complex, as is the Wolf-Rayet star HD 93162 = WR 25 (WN7 + abs). Massey & Johnson (1993) provide a modern CCD study of this region, including spectroscopy of many of the brightest blue stars, concluding that Tr 14 and Tr 16 were at identical distance and were coeval. A comprehensive study of the fainter members is given by DeGioia-Eastwood et al. (2001), who study several background fields in order to recognize pre–main-sequence objects in the H-R diagram.

2.3.4. *Pismis 20 (C1511−588)*

The only previous photometry of Pis 20 is the photographic study by Moffat & Vogt (1973). WR 67 = HD 134877 = Pis 20-8 (WN6) is nearly 2′ from the central core of the cluster, which is heavily concentrated in a region roughly 1′ in diameter. We derive a distance modulus of 12.7 mag (3.5 kpc) for the cluster, and an average reddening of $E(B-V) = 1.1$, with little scatter. The reddening of WR 67 given by Conti & Vacca (1990) is identical to this value, and we find $M_v = -5.1$, consistent with that expected for a WN6 star (Table 2 of Conti & Vacca 1990). We conclude that WR 67 is a member. Van der Hucht et al. (1981) also list WR 66 as a possible member, but its location some 46′ south of the cluster makes this extremely unlikely.

2.3.5. *C1715−387*

The cluster C1715−387 was studied by Havlen & Moffat (1977), who identified 15 members and nine nonmembers from their photoelectric *UBV* photometry. The cluster

[8] It is worth noting that our method of deriving the distances and reddenings makes our results completely independent of any zero-point errors in the photometry, either in V or even $B-V$. For instance, imagine that the published photometry was in error by 0.1 mag in V ($V_{\rm true} = V_{\rm publ} + 0.1$) and by +0.1 mag in $B-V$ [$(B-V)_{\rm true} = (B-V)_{\rm publ} + 0.1$]. The extinction correction $A_V = 3.2E(B-V)$ will be underestimated by 0.32 mag, and the V_0 we compute will be too large by 0.22 mag, and our value for the distance modulus too small by 0.22 mag. However, when we go to use this incorrect distance modulus with the rest of the photometry, for which we do not have spectral types, it exactly compensates for the systematic photometric errors, reproducing the correct values for M_V and $(B-V)_0$. This is of course because we determined the distance modulus and reddening that caused us to match the correct (adopted) M_V and $(B-V)_0$ based upon the spectral type. In a reductio ad absurdum, the V magnitudes could be off by 10 mag, and the $B-V$ values off by 1 mag, and although our distance moduli would be ridiculous, we would nevertheless be able to construct accurate H-R diagrams, as long as the *relative* V magnitudes and *relative* $B-V$ values are correct. It is easy to extend this argument to $U-B$ and the color-free index $q_r = E(U-B)/E(B-V)$, which we will in fact use. In practice, errors in the published photometry probably include color terms as well. Redoing the photometry for the clusters using modern CCD techniques would be well worthwhile, but primarily for improving our knowledge of Galactic structure—refinements in the distance moduli and actual reddenings will have little effect on our H-R diagrams.

appears to contain two Wolf-Rayet stars, WR 89 (=LSS 4065 = C1715−387 No. 1), of type WN7,[9] and WR 87 (=LSS 4064 = C1715−387 No. 3), also of type WN7. Their spectroscopy identified several early-type O stars, including two early O-type supergiants: star 2 (=LSS 4067), an O4 If, and star 6, an O5 If, both of which we confirm. They derive a distance modulus of 12.6 ± 0.3 mag (3.3 kpc) via main-sequence fitting and 12.0 ± 0.3 mag (2.5 kpc) via spectroscopic parallax, adopting a compromise 12.3 ± 0.3 mag [*sic*] (2.9 kpc). Thé, Arens, & van der Hucht (1982) obtained Walraven system photoelectric photometry of these plus additional members and conclude that the distance modulus cannot be determined with any certainty from the photometry alone.

We have obtained spectra for five of the stars, all of which are of O type, ranging from O4 If to O9.5 III. Four out of the five stars have nearly identical reddenings, with $E(B-V) = 1.85 \pm 0.03$; the O9.5 III has a smaller value, $E(B-V) = 1.65$. The reddening is peculiar toward C1715−387, or else there is a significant zero-point problem in one (or both) of the colors given by Havlen & Moffat (1977). A value of $q_r = 0.83$ is suggested for most of the stars, but a value nearer the canonical 0.72 is indicated by the less reddened O9.5 III star.

If we take only the two O dwarfs, we find a distance modulus of 12.0 mag; the distances of the supergiants are consistent with this, although they would nominally suggest a distance modulus of 12.2 mag. We adopt a distance modulus of 12.0 mag (2.5 kpc), identical to the value obtained by Havlen & Moffat (1977) using the same data but with less complete spectroscopic data.

Thé et al. (1982) suggested that one of the stars (their No. 35) is an M-type supergiant with rather low absolute luminosity ($M_{\rm bol} = -6.3$, adjusted for our closer distance modulus), where the bolometric correction was adopted apparently assuming that the star is M0. If so, the star cannot be coeval with the rest of the cluster, given the H-R diagrams we derive subsequently. We note that there is no spectroscopy of this star, only photometry, and the star could simply be a foreground dwarf. Or, if the star is a *late*-type M supergiant, then its bolometric luminosity might be a couple of magnitudes more negative.

2.3.6. *Pismis 24 (C1722−343)*

Moffat & Vogt (1973) obtained photometry of 15 stars in Pis 24, 12 of which they concluded are members. We obtained spectroscopy of 11 stars, four of which were not included in their list. We find that two of the cluster stars are of type O3, one of which is a supergiant (HDE 319718 = Pis 24-1) and the other of which appears to be a giant (what we now call Pis 24-17); these stars were discussed in § 2.2.1. Most of the rest are found to be of O type, although we do reach B dwarfs. Thus this is a highly interesting cluster, and additional photometry and spectroscopy are highly warranted.

For HDE 319718, we note that the $V = 10.01$ photometry given by Crampton (1971) is at variance with the $V = 10.43$ photometry of Moffat & Vogt (1973) by 0.4 mag. In addition, there are 0.1 mag differences in the colors. Lortet et al. (1984) describe this star as "O4(f)" and state that the radial velocity changed by 94 km s^{-1} during a few days, so possibly the light variation was real. However, there is also photoelectric photometry by Neckel (1978). His value of $V = 10.27$ is probably consistent with that of Moffat & Vogt, as Neckel used a large aperture that would have included some of the companion stars (see discussion in Lortet et al. 1984).

The cluster is associated with the nebula NGC 6357, a large shell with "several roundish nebulae" (Lortet et al. 1984). The brightest of these is near Pis 24.

In order to provide V and $B-V$ photometry for the four additional stars, we obtained images in B and V with the WIYN 3.5 m telescope on 1998 September 29. The field of view was 6.′7 on a side with a scale of 0.″2 pixel^{-1}. At air masses in excess of 3, the image quality was poor, about 2.″6. We obtained photometry differentially relative to the stars with photoelectric photometry by Moffat & Vogt (1973). The 1 σ scatter from five stars was 0.03. We refer to the four new stars as 16–19; all four are located near star HDE 319718, with a pair 15″ to the east and a pair 15″ to the north. The pair to the east we label 16 (northwest of pair) and 17 (southeast). The pair to the north we label 18 (west of pair) and 19 (east). These stars are clearly visible in Figure 4*a* of Lortet et al. (1984); our star Pis 24-17 is the one they label "N35B," and classified as O4–O5 V, although our better sky-subtracted spectrum reveals that it is of O3 III(f*) type (§ 2.2.1).

If we use the 10 stars with certain luminosity classes to compute the spectroscopic parallax, we find a distance modulus of 12.03 ± 0.14 mag (s.d.m.). If we use only the six O dwarfs to derive the distance, we compute 11.99 ± 0.05 mag (s.d.m.). We adopt a true distance modulus of 12.0 mag (2.5 kpc), somewhat further than the 1.7 kpc suggested by Neckel (1978) and Lortet et al. (1984).

The cluster contains the Wolf-Rayet star HD 157504 (WR 93), of type WC7. Such late-type WC stars are unknown in the Magellanic Clouds and are found primarily inward of the Sun in the Milky Way. Conti & Vacca (1990) describe this star as a "WCE + abs" and derive a distance of 1.1 kpc, considerably closer than the 2.5 kpc we find for the cluster. This includes a very large correction ($A_V = 5.9$ mag) for interstellar extinction. The star is located 4′ west of the central cluster, which is otherwise extended over 5′ north-south, but 1′–2′ east-west. However, it is not clear what photometry over a larger field would reveal: At this distance, 5′ corresponds to 4 pc, while stellar drifts over 1 Myr would extend to 10 pc at 10 km s^{-1}. Thus, the cluster might well be larger than indicated. We consider HD 157504 a likely member of Pis 24.

2.3.7. *Trumpler 27 (C1732−334)*

Thé & Stokes (1970) studied the cluster Tr 27 by means of photoelectrically calibrated photographic *UBV* photometry, identifying many highly reddened early-type stars and deriving a true distance modulus of 10.2 mag (1.1 kpc) based upon main-sequence fitting. Moffat, FitzGerald, & Jackson (1977) obtained photoelectric *UBV* data and some

[9] Walborn & Fitzpatrick (2000) recently classified this star as "WN8-A." After N. Walborn kindly called the matter to our attention, we reexamined our own higher S/N spectrum of this star, and we find that we are in accord with the WN7 classification given by van der Hucht et al. (1981). One may compare the Walborn & Fitzpatrick (2000) spectrum with that of the spectral WN8 standard HD 177230 shown by Massey & Conti (1980). We would argue that the WN7 classification of LSS 4065 is slightly preferred over WN8 given the lack of He I P Cygni emission (and general weakness of the He I emission), plus the relative intensity of N III λλ4634, 4642 emission relative to He II λ4686.

objective-prism (and a few slit) spectral types; they derive a distance modulus of 11.7 ± 0.2 mag (2.1 kpc) based upon spectroscopic parallax. We note here that the difference between the photographic and photoelectric V magnitudes shows a strong magnitude dependence, and that there are significant color terms between the photographic and photoelectric $B-V$ values, which partially explains the difference in the derived distances. Bakker & Thé (1983) used the Walraven photometric system to determine a distance modulus of 11.2 mag (1.7 kpc), citing the poorly known absolute magnitude calibration for supergiants to explain the difference between their and Moffat et al.'s results.

We have new spectral types for 12 OB stars, eight of which are in common with previous slit spectroscopy by Moffat et al. (1977). Unfortunately, all but one of these are giants and supergiants, which intrinsically exhibit a large range in M_V. For instance, a B0 I could easily range from $M_V = -6$ to $M_V = -7$ (Humphreys & McElroy 1984). Our spectroscopy suggests a distance modulus of 12.0 ± 0.3 mag (2.5 kpc), slightly greater than the Moffat et al. value. The region is ripe for a CCD study and spectroscopy that reaches the dwarfs.

The cluster contains two Wolf-Rayet stars, WR 95 (=Tr 27-28), of type WC9, and WR 98 (=MR 76=Tr 27-105), of type WC7/WN6. Conti & Vacca (1990) infer their distances as 2.8 and 2.4 kpc, respectively, consistent with the distance we find from spectroscopic parallax of the OB stars. The region also contains two other evolved stars: Tr 28-1 is of type M0 Ia (Imhoff & Keenan 1976), and Tr 28-102 is of type G0 Ia (Moffat et al. 1977). Dereddening the stars using the intrinsic colors of FitzGerald (1970), we find absolute visual magnitudes of -7.9 and -6.9. The former is consistent with an extreme M-type supergiant; Imhoff & Keenan (1976) estimate the star's absolute magnitude as -7.2 ± 0.5 from coudé spectroscopy of luminosity-sensitive features. The M_V expected from a "G0 Ia" star is -7.5 (cf. Humphreys & McElroy 1984), although G supergiants cover a 5 mag range in luminosity depending upon whether the "a" could be a "b" or not! We conclude that a value $(m-M)_0 = 12.0$ is consistent with both the W-R stars' and the two other supergiants' being members.

The data here suggest a significant age spread for the cluster. The G0 Ia star falls near the 10 Myr isochrone, and the two B8 I stars classified have ages of 6 Myr, considerably older than the 2–4 Myr age suggested by the rest of the stars. We suggest that this apparent "age spread" is due to the difficulty of separating real cluster members from background objects. For instance, the two early B-type stars Tr 27-44 and Tr 27-107 both have absolute visual magnitudes corresponding to *giants* rather than *supergiants* if we assume they are indeed cluster members. However, their spectra both indicate an extremely high luminosity class (Ia), with a rich assortment of strong, narrow metal lines. We believe these two stars are actually background objects, suggesting that other apparent cluster members may be unassociated with the cluster instead. We include these two stars in the H-R diagram, as their implied masses are too low to affect our judgment of the W-R progenitor masses.

2.3.8. *NGC 6871* (*C2004+356*)

The long-period (119 day) Wolf-Rayet binary HD 190918 (WN4.5 + O9 Ia) is part of the large NGC 6871 complex. The region was included in Massey et al. (1995a). No brightness ratio of the O9 Ia to the WN4.5 star has been published; however, even a casual inspection of the spectrum suggests that the O9 Ia star dominates the continuum. For the purposes of including the O9 Ia star in the H-R diagram, we make the very conservative assumption that the light of the two components contributes equally; however, even in the extreme case that we assign *all* of the light to the O9 Ia star, this component is not the most massive present in the cluster.

We note that the cluster also contains the famous X-ray binary and black hole candidate Cyg X-1. The inferred mass of the O9.7 Ia component makes it one of the two most massive objects in the cluster, consistent with the highly evolved state of its companion. Spectral analysis of the star led Herrero et al. (1995) to conclude that the star has a mass of 17–20 $M_\odot$, considerably less than the 40 $M_\odot$ we would deduce here, but this is consistent the fact that other short-period binaries also show a similar "mass discrepancy" between the evolutionary tracks and those inferred from other means (Burkholder, Massey, & Morrell 1997), suggesting that mass has been lost via Roche lobe overflow in such systems.

2.3.9. *Berkeley 86* (*C2018+385*)

The cluster Berk 86 was included in the Massey et al. (1995a) study, and we have not acquired any new data. It contains one of the well known Wolf-Rayet eclipsing binaries, V444 Cyg (WN5 + O6). The O6 component is the most massive star in the cluster, as judged from the H-R diagram, if we assume a ratio of 0.6 for the luminosity of the WN5 star to that of the O6 star (Cherepashchuk et al. 1995).

2.3.10. *Berkeley 87* (*C2019+372*)

The cluster Berk 87 was studied photoelectrically and photographically by Turner & Forbes (1982). The WC5 star ST 3 (WR 142) is located very near the cluster center (star 29 in Fig. 1 of Turner & Forbes). Previously, spectroscopy had identified a B2 I (Berk 87-3) and an O9 V (Berk 87-25) star among its other members; we have obtained new spectral types for these and 11 other members. The implied spectroscopic parallax is 11.0 mag, and a slightly high $q_r = 0.84$ value is found. All stars fall into a narrow range in $E(B-V)$. We find that one of our stars is a B[e] star.

2.3.11. *Cygnus OB2*

The Cyg OB2 association contains many early-type stars, including one of the rare O3 If* (Walborn 1973b). It was scrutinized both photometrically and spectroscopically by Massey & Thompson (1991). Van der Hucht et al. (1981) list three Wolf-Rayet stars as members, but of these only WR 144 lies near the 50′ (east-west) by 40′ (north-south) region examined by Massey & Thompson. WR 145 lies 30′ south and 16′ west of the concentration of bright blue stars (Fig. 9 of Massey & Thompson 1991), and WR 146 lies 29′ east. The V magnitude of WR 145 is consistent with membership, although the lack of color information and wide range of reddenings makes membership difficult to determine. Only WR 145 has line-free photometry, and its estimated distance is 0.5 kpc (Conti & Vacca 1990), considerably at variance with the 1.7 kpc distance derived by Massey & Thompson. For the sake of this study, we will make the conservative assumption that only WR 144 is a likely member.

Massey & Thompson (1991) argue that the star VI Cyg No. 12 has many of the characteristics of an LBV: it is extremely luminous bolometrically ($M_{\rm bol} \approx -11$), and its absolute visual magnitude may be unequaled ($M_V \approx -10$). It is known to be both spectroscopically and photometrically variable. Humphreys & Davidson (1994) characterize the star an "A-type hypergiant" (the spectral type is B5 Ie according to Massey & Thompson) and argue that it is "not [a] full-fledged LBV." Here we continue to consider it at least an "LBV candidate."

2.3.12. *Markarian 50* (*C2313+602*)

As described by Crampton (1975), the Wolf-Rayet star HD 219460 (WN4.5) was found to lie near the center of a concentration of early-type stars by Markarian (1951). Photographic photometry and a finding chart were given by Grubissich (1965). Crampton (1975) obtained spectra of eight stars (two of which were foreground) and derived a distance modulus of 12.0 mag (2.5 kpc). Turner et al. (1983) obtained photoelectric photometry for some of the stars and a multitude of spectra for the W-R star, which was blended with a B-type visual companion (separation 1″), which they classify as B1 II. They find a distance modulus of 12.75 ± 0.12 mag (3.6 kpc), using a combination of main-sequence fitting and spectroscopic parallax. Our new spectroscopic distance modulus of 12.79 ± 0.1 mag is in good agreement with this value.

3. THE HERTZSPRUNG-RUSSELL DIAGRAMS: IDENTIFYING THE HIGHEST MASS STARS AND TESTS OF COEVALITY

With the reddenings and distances of § 2.2.2, we can now transform to the H-R diagram using the methods described in Paper I. Since we successfully obtained spectral types for nearly all of the brighter stars in each cluster (e.g., Table 2), we rely upon the MK type to give us the effective temperature. Since the reddening is potentially variable across each cluster, we use the intrinsic color as a function of spectral type along with the observed photometry to correct the V magnitude for interstellar extinction and then use our adopted distance modulus (Table 1) to determine M_V. The bolometric correction comes from the adopted effective temperature, yielding the bolometric luminosity. Reference to the evolutionary tracks of Schaller et al. (1992), computed for $Z = 0.020$, provides both the *zero age* masses and the *ages* of the stars.

We show in Figure 3 the H-R diagrams for the eight clusters for which we have new data; similar diagrams, made with the identical transformations, can be found for Tr 14, NGC 6871, Berk 86, and Cyg OB2 in Massey et al. (1995a; see Massey et al. 1995b and Massey 1998c for a

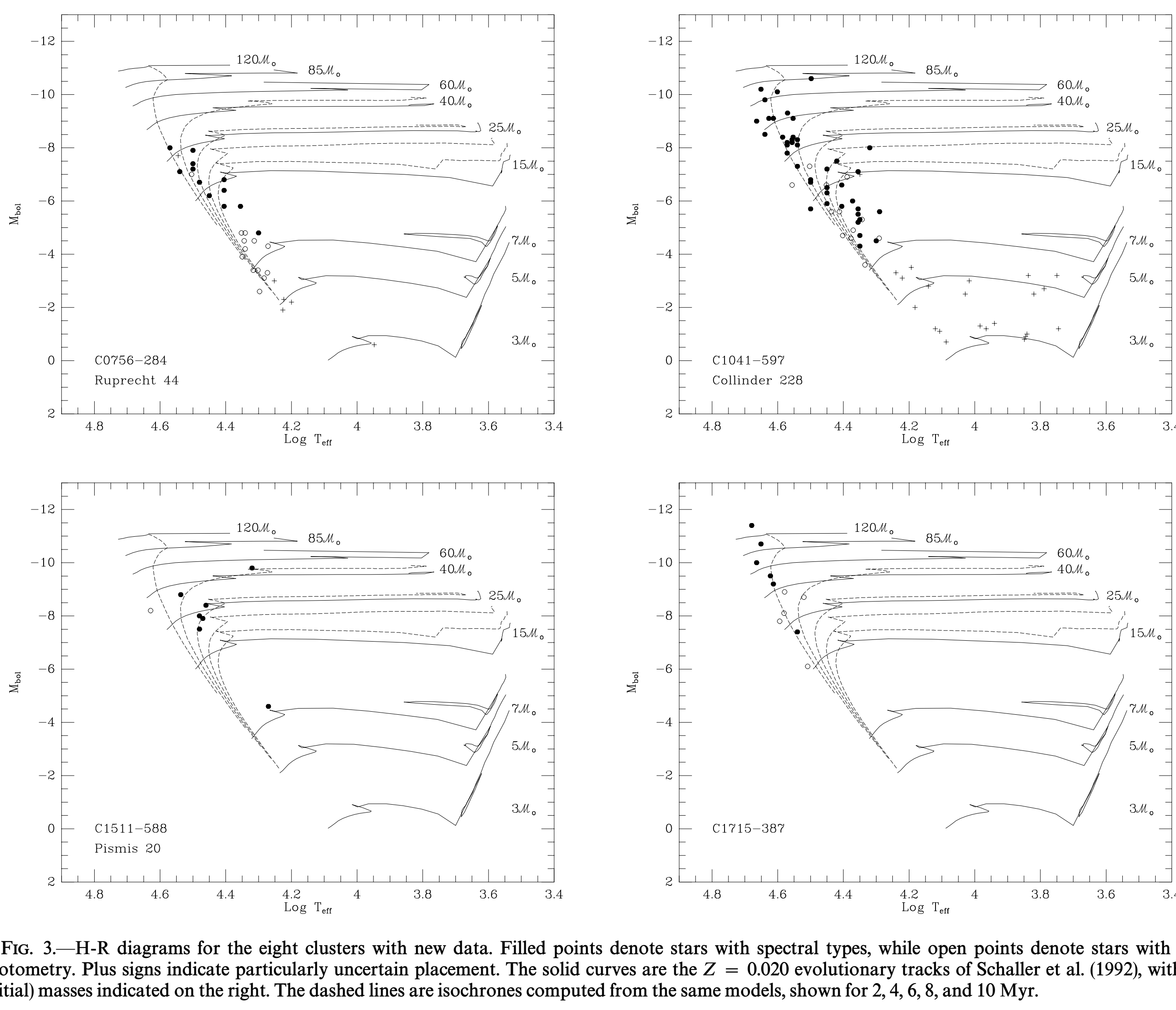

FIG. 3.—H-R diagrams for the eight clusters with new data. Filled points denote stars with spectral types, while open points denote stars with only photometry. Plus signs indicate particularly uncertain placement. The solid curves are the $Z = 0.020$ evolutionary tracks of Schaller et al. (1992), with the (initial) masses indicated on the right. The dashed lines are isochrones computed from the same models, shown for 2, 4, 6, 8, and 10 Myr.

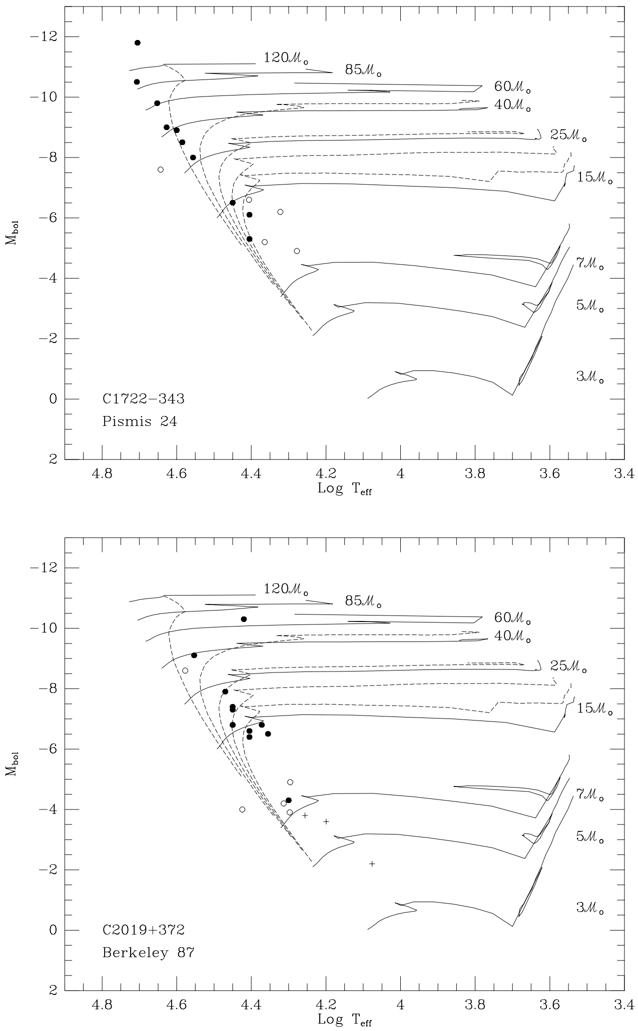

FIG. 3.—*Continued*

discussion of the associated errors). We can use these data to identify the highest mass stars and consider whether the degree of coevality allows the current "turnoff" masses to have relevance to the progenitor masses of the associated W-R stars.

We list in Table 3 the highest mass stars in each cluster, along with their ages, both according to the evolutionary tracks. As is evident from Figure 3, the highest mass unevolved stars range considerably from cluster to cluster, with the youngest (0.3 Myr), Tr 14, having stars well in excess of the 120 $M_\odot$ highest mass tracks computed by the Geneva group. (Using a very conservative estimate of the mass-luminosity relation, we estimate that the highest mass star there corresponds to an initial mass of 185 $M_\odot$, with the next highest mass star being 130 $M_\odot$.) The oldest cluster (8 Myr), Markarian 50, contains stars no more massive than 20 $M_\odot$. This spread in turnoff masses is considerably larger than we saw in the Magellanic Clouds; we discuss this further in § 4.

We caution the unwary not to use the data in Table 3 to compare the IMFs of these clusters. Although the data discussed in Massey et al. (1995a) are adequate for those purposes, the data presented here for the eight clusters with new data are not, primarily because of the scant amount (and poor quality) of the photometry. A project is underway at Lowell Observatory and CTIO to rectify this situation.

The H-R diagrams in Figure 3 give readers a chance to judge the extent of coevality of each of these clusters. In Paper I, we also offered a more rigorous criterion on which to judge the extent of coevality. We can use the same test here. Let us begin by assuming that the typical *error* in assigning a star's location in the H-R diagram corresponds to *one spectral type*. (This error is considerably less than that resulting from the use of photometry alone for high-mass, hot stars, as shown graphically by Massey et al. 1995b, Figs. 1*c* and 1*d*; see also derivation in Massey 1998c.) We can now ask what fraction of the stars, above some mass, are consistent with the cluster's being strictly coeval (e.g., the data being consistent with all the high-mass stars having been "born on a particular Tuesday," as Hillenbrand et al. 1993 put it). We again restrict ourselves to those stars of mass 20 $M_\odot$ and above, as there is a systematic difference between the zero-age main sequence and the transformed locations in the H-R diagram (see Fig. 8 in Paper I and the corresponding discussion). In addition, let us compare the median age of the three highest mass stars with the median age of the entire cluster ($>20\ M_\odot$). We give the results in Table 4.

As in Paper I, we find excellent agreement between our *impressions* from the H-R diagrams and the *quantitative determination* from Table 4. If the disagreement between the median cluster age for all stars with masses greater than 20

TABLE 3

Derived Parameters for the Highest Mass Unevolved Stars

Association	log T_{eff}	M_V	M_{bol}	Mass ($M_\odot$)	Age (log yr)	Spectral Type and/or Comment
Ruprecht 44:						
LSS 891	4.570	−4.4	−8.0	27	6.34	O8 III(f)
LSS 898	4.545:	−4.3	−7.7:	24:	6.52:	Be
LSS 902	4.500	−4.7	−7.9	23	6.72	B0 V
Ru 44-920	4.540	−3.7	−7.1	21	6.21	O9.5 V
LSS 907	4.500	−4.3	−7.4	20	6.73	B0 V
Collinder 228:						
HD 93206	4.498	−7.5	−10.6	88	6.37	O9.5 I
HD 93632	4.657	−6.1	−10.2	76	6.12	O5 III(f)
HD 93130	4.601	−6.3	−10.1	68	6.33	O7 II(f)
HDE 305525	4.639	−5.7	−9.8	58	6.21	O6 V
Cr 228-97	4.664	−4.8	−9.0	47	5.61	O5 V
HD 93146	4.627	−5.1	−9.1	44	6.15	O6.5 V((f))
HDE 305524	4.613	−5.2	−9.1	42	6.29	O7 V((f))
HD 93222	4.570	−5.7	−9.3	42	6.47	O8 III((f))
HDE 305523	4.553	−5.6	−9.1	38	6.52	O8.5 III
HDE 305532	4.639	−4.4	−8.5	38	5.68	O6 V((f))
HDE 305438	4.585	−4.6	−8.4	32	6.34	O8 V
HD 93028	4.553	−4.9	−8.4	30	6.54	O8.5 III
HDE 305518	4.540	−5.0	−8.3	29	6.59	O9.5 V
HD 93027	4.556	−4.8	−8.3	29	6.53	O9 V
Cr 228-39	4.571	−4.6	−8.2	29	6.42	O8.5 V((f))
HDE 305539	4.571	−4.4	−8.1	28	6.37	O8.5 V
Cr 228-67	4.556	−4.7	−8.2	28	6.52	O9 V
HD 93576	4.556	−4.7	−8.2	28	6.52	O9 V
Cr 228-21	4.571	−4.2	−7.8	27	6.26	O8.5 V
HDE 305536	4.540	−4.7	−8.1	26	6.59	O9.5 V
Cr 228-66	4.540	−3.9	−7.3	22	6.37	O9.5 V
Cr 228-12	4.320	−6.1	−8.0	20	6.90	B2.5 Ia:
Trumpler 14/16:						
HD 93129AB	4.705	−7.5	−12.1	>120	5.94	O3 If*
HD 93250	4.710	−6.7	−11.3	>120	5.76	O3 V
HD 93205	4.710	−6.1	−10.7	104	5.46	O3 V
HDE 303308	4.710	−5.9	−10.4	93	5.45	O3 V
HD 93128	4.710	−5.4	−10.0	75	5.49	O3 V
HD 93160	4.630	−5.9	−9.9	62	6.26	O6 III
HD 93204	4.664	−5.4	−9.6	59	5.86	O5 V
CPD −59°2600	4.639	−5.5	−9.6	55	6.19	O6 V
HDE 303311	4.664	−5.0	−9.2	51	5.59	O5 V
CPD −59°2641	4.639	−5.2	−9.3	49	6.09	O6 V
Tr 14-257	4.679	−4.3	−8.7	44	5.63	O4 I
CPD −59°2603	4.613	−5.2	−9.1	43	6.29	O7 V
CPD −58°2611	4.639	−4.6	−8.6	39	5.66	O6 V
Tr 14-404	4.600:	−5.0	−8.8:	37:	6.33:	Photometry only
CPD −59°2636	4.585	−5.2	−8.9	37	6.43	O8 V
Tr 14-484	4.613	−4.8	−8.7	37	6.13	O7 V
HD 93343	4.613	−4.7	−8.6	37	6.11	O7 V
CPD −58°2620	4.627	−4.3	−8.3	35	5.71	O6.5 V
Tr 14-165	4.585	−4.8	−8.5	34	6.39	O8 V
Tr 14-36	4.639:	−4.0	−8.1:	33:	5.73:	Photometry only
Tr 14-593	4.611:	−4.3	−8.2:	33:	5.74:	Photometry only
CPD −59°2635	4.571	−5.0	−8.6	33	6.48	O8.5 V
Tr 14-449	4.626:	−4.0	−7.9:	31:	5.76:	Photometry only
Tr 14-203	4.600:	−4.1	−7.9:	29:	5.79:	
Tr 14-359	4.585	−4.0	−7.7	27	5.83	O8 V
Tr 14-117	4.540	−4.8	−8.2	27	6.59	O9.5 V
Pismis 20:						
HD 134959	4.320	−7.9	−9.8	50	6.56	B2.5 Ia
Pis 20-6	(4.629:)	−4.2	(−8.2:)	(34:)	(<1)	Early B
Pis 20-2	4.537	−5.4	−8.8	34	6.57	O8.5 I
Pis 20-3	4.460	−5.5	−8.4	26	6.77	B0 I
Pis 20-7	4.480	−5.0	−8.0	23	6.76	B0 III
Pis 20-4	4.470	−5.0	−7.9	23	6.78	B0.2 III
Pis 20-5	4.480	−4.5	−7.5	20	6.79	B0 III

TABLE 3—*Continued*

Association	log T_{eff}	M_V	M_{bol}	Mass ($M_\odot$)	Age (log yr)	Spectral Type and/or Comment
C1715−387:						
LSS 4067	4.679	−7.0	−11.4	120	6.04	O4 If+
C1715−387 No. 6	4.651	−6.5	−10.7	95	6.15	O5 If
C1715−387 No. 8	4.664	−5.7	−10.0	68	6.01	O5 V
C1715−387 No. 12	4.622	−5.5	−9.5	50	6.28	O6 If
C1715−387 No. 13	4.613	−5.3	−9.2	44	6.30	O7 V((f))
C1715−387 No. 9	4.579:	−5.3	−8.9:	38:	6.45:	Photometry only
C1715−387 No. 16	4.520:	−5.4	−8.7:	32:	6.61:	Photometry only
C1715−387 No. 18	4.581:	−4.4	−8.1:	29:	6.26:	Photometry only
C1715−387 No. 19	4.594:	−4.1	−7.8:	28:	5.80:	Photometry only
C1715−387 No. 20	4.540	−4.1	−7.4	22	6.47	O9.5 V:
Pismis 24:						
HDE 319718	4.705	−7.3	−11.8	120	5.86	O3 If*
Pis 24-17	4.707	−6.0	−10.5	98	5.46	O3 III(f*)
Pis 24-2	4.652	−5.6	−9.8	60	6.11	O5.5 V((f))
Pis 24-13	4.627	−5.1	−9.0	43	6.14	O6.5 V((f))
Pis 24-16	4.600	−5.1	−8.9	39	6.35	O7.5 V
Pis 24-3	4.585	−4.8	−8.5	33	6.37	O8 V
Pis 24-15	4.585	−4.8	−8.5	33	6.37	O8 V
Pis 24-10	4.556	−4.5	−8.0	27	6.48	O9 V
Trumpler 27:						
Tr 27-27	4.570	−6.9	−10.5	81	6.32	O8 III((f))
Tr 27-23	4.440	−7.5	−10.2	64	6.47	B0.5 I
Tr 27-2	4.460	−6.5	−9.4	42	6.58	B0 Ia
Tr 27-46	4.050	−8.7	−9.3	35	6.68	B8 I
Tr 27-104	4.553	−5.1	−8.6	32	6.54	O8.5 III
Tr 27-43	4.050	−8.2	−8.9	29	6.76	B8 I
Tr 27-14	4.460	−5.7	−8.5	27	6.75	B0 Ib
Tr 27-16	4.440	−5.7	−8.5	26	6.79	B0.5 Ia
Tr 27-1a	4.563:	−3.8	−7.4:	23:	5.89:	Photometry only
Tr 27-103	4.420	−5.4	−7.9	21	6.88	B1 I
NGC 6871:						
HD 190864	4.601	−5.5	−9.3	45	6.37	O7 III
HD 226868	4.518	−6.4	−9.6	(40)	(6.51)	O9.7 I
HD 227018	4.613	−4.9	−8.8	38	6.20	O7 V
HD 191201	4.500	−5.8	−8.9	35	6.62	B0 V
HD 190918 companion	4.498	−5.4::	−8.5::	29::	6.67::	O9.5 I W-R companion
HD 227634	4.470	−5.3	−8.2	25	6.75	B0.2 III
HD 190919	4.420	−5.8	−8.3	25	6.81	B1 Ib
BD +35°3955	4.420	−5.7	−8.3	24	6.83	B1 Ib
Berkeley 86:						
V444 Cyg companion	4.630::	−5.5::	−9.6::	53:	6.24:	O6 III W-R companion
HD 228841	4.613	−5.4	−9.3	45	6.31	O7 V
HD 193595	4.585	−4.9	−8.6	34	6.39	O8 V
HD 228969	4.540	−5.0	−8.4	30	6.59	O9.5 V
HD 228943	4.500	−5.3	−8.4	28	6.68	B0 V
Berkeley 87:						
HDE 229059	4.420	−7.7	−10.3	69	6.46	B1 Ia
Berk 87-25	4.553	−5.6	−9.1	39	6.51	O8.5 III
Berk 87-15	4.577:	−5.0	−8.6:	34:	6.45:	B[e]
Berk 87-4	4.470	−5.0	−7.9	23	6.78	B0.2 III
Cygnus OB2:						
Cyg OB2-516	4.652	−7.4	−11.6	>120	6.29	O5.5 V((f))
Cyg OB2-431	4.651	−7.0	−11.2	>120	6.16	O5 If
Cyg OB2-417	4.683	−7.2	−11.6	>120	6.03	O4 III(f)
Cyg OB2-465	4.637	−7.3	−11.3	>120	6.32	O5.5 I(f)
Cyg OB2-734	4.651	−6.9	−11.1	>120	6.15	O5 If
Cyg OB2-457	4.705	−6.3	−10.8	114	5.67	O3 If
Cyg OB2-304	4.270	−10.6	−12.2	92	6.43	B5 Ie
Cyg OB2-771	4.613	−6.7	−10.6	90	6.26	O7 V
Cyg OB2-462	4.616	−6.5	−10.4	80	6.26	O6.5 III((f))
Cyg OB2-632	4.498	−7.3	−10.4	75	6.40	O9.5 I
Cyg OB2-483	4.651	−6.0	−10.1	71	6.15	O5 If
Cyg OB2-448	4.639	−5.5	−9.6	54	6.17	O6 V ((f))
Cyg OB2-217	4.601	−5.8	−9.6	52	6.37	O7 III ((f))
Cyg OB2-555	4.585	−5.8	−9.5	48	6.42	O8 V

TABLE 3—*Continued*

Association	log T_{eff}	M_V	M_{bol}	Mass ($M_\odot$)	Age (log yr)	Spectral Type and/or Comment
Cyg OB2-138	4.537	−6.2	−9.6	48	6.49	O8.5 I
Cyg OB2-70	4.556	−5.9	−9.4	46	6.48	O9 V
Cyg OB2-390	4.585	−5.6	−9.3	44	6.42	O8 V
Cyg OB2-480	4.600	−5.4	−9.2	44	6.37	O7.5 V
Cyg OB2-59	4.571	−5.7	−9.3	44	6.46	O8.5 V
Cyg OB2-531	4.571	−5.6	−9.2	42	6.47	O8.5 V
Cyg OB2-317	4.585	−5.5	−9.2	42	6.43	O8 V
Cyg OB2-745	4.613	−5.1	−9.0	41	6.28	O7 V
Cyg OB2-299	4.600	−5.2	−9.0	40	6.36	O7.5 V
Cyg OB2-534	4.600	−5.2	−9.0	40	6.36	O7.5 V
Cyg OB2-5	4.639	−4.5	−8.6	39	5.66	O6 V((f))
Cyg OB2-601	4.518	−5.8	−9.0	37	6.58	O9.5 III
Cyg OB2-421	4.540	−5.6	−9.0	37	6.55	O9.5 V
Cyg OB2-455	4.585	−5.1	−8.8	36	6.42	O8 V
Cyg OB2-258	4.585	−4.9	−8.6	35	6.40	O8 V
Cyg OB2-485	4.585	−5.0	−8.7	35	6.40	O8 V
Cyg OB2-611	4.613	−4.4	−8.3	34	5.73	O7 Vp
Cyg OB2-556	4.420	−6.5	−9.0	33	6.70	B1 Ib
Cyg OB2-339	4.571	−4.9	−8.5	32	6.47	O8.5 V
Cyg OB2-473	4.571	−4.8	−8.4	31	6.46	O8.5 V
Cyg OB2-696	4.540	−5.1	−8.5	31	6.59	O9.5 V
Cyg OB2-376	4.585	−4.6	−8.3	31	6.32	O8 V
Cyg OB2-378	4.500	−5.4	−8.5	29	6.67	B0 V
Cyg OB2-227	4.556	−4.7	−8.2	28	6.52	O9 V
Cyg OB2-507	4.571	−4.4	−8.0	28	6.36	O8.5 V
Cyg OB2-716	4.556	−4.6	−8.1	27	6.51	O9 V
Cyg OB2-588	4.500	−5.1	−8.2	26	6.70	B0 V
Cyg OB2-736	4.556	−4.1	−7.6	24	6.33	O9 V
Cyg OB2-470	4.540	−4.3	−7.7	24	6.55	O9.5 V
Cyg OB2-425	4.500	−4.7	−7.9	23	6.72	B0 V
Cyg OB2-145	4.540	−4.2	−7.6	23	6.52	O9.5 V
Cyg OB2-426	4.500	−4.3	−7.5	21	6.73	B0 V
Cyg OB2-429	4.500	−4.2	−7.3	20	6.72	B0 V
Markarian 50:						
HD 219460A	4.480	−4.7	−7.7	21	6.79	B0 III (W-R visual companion)
Ma 50-31	4.450	−4.6	−7.4	19	6.87	B0.5 I
Ma 50-23	4.372	−4.5	−6.7	14	7.11	B1 III
Ma 50-30A	4.350	−3.6	−5.7	11	7.23	B1.5 V
Ma 50-1	4.350	−2.8	−4.8	9	7.24	B1.5 V

$M_\odot$ (as determined for the stars with spectral types) and the median ages of the three highest mass stars differs by more than 0.2 dex, we suspect the cluster may not be coeval. Or, if less than 80% of the stars are consistent with a maximum age spread of 1 Myr, we consider the degree of coevality marginal. Only Tr 27 and NGC 6871 fail both these tests. As we discussed above, this does not necessary reveal that the star formation process for the massive stars lasted significantly longer here than for the other clusters—in the case of Tr 27 we suspect that much of the problem is confu-

TABLE 4

COEVALITY AND CLUSTER AGES AND TURNOFF MASSES

Association	Median Age (log yr): All $>20\ M_\odot$	Median Age (log yr): Three Highest Mass	Coevality: Percentage	Coevality: Conclusion	Cluster Turnoff: Mass ($M_\odot$)	Cluster Turnoff: Comments
Ru 44	6.53	6.34	100	Yes	25	H-R diagram looks coeval
Cr 228	6.37	6.33	86	Yes	90	H-R diagram implies some age spread
Tr 14/16	6.14	5.94	81	Yes	>120	
Pis 20	6.77	6.56	67	Questionable	50	H-R diagram looks coeval
C1715−387	6.22	6.04	100	Yes	>120	H-R diagram very coeval
Pis 24	6.24	(5.86)	100	Very likely	>120	
Tr 27	6.72	6.47	70	No	80	Contaminated by noncluster stars?
NGC 6871	6.64	6.37	75	No	45	
Berk 86	6.53	6.39	100	Yes	50	
Berk 87	6.51	6.51:	100	Yes	70	Only three stars in sample
Cyg OB2	6.42	6.16	94	Questionable	>120	Many high-mass stars of similar ages
Ma 50	6.87	6.87	100	Yes	20	Used $\geq 15\ M_\odot$

sion by background supergiants. By our stringent criteria we list the coevality of Pis 20 and Cyg OB2 as questionable, failing one of the two tests, although inspection of the H-R diagrams suggests that most of the highest mass stars in these regions are in fact coeval.

4. RESULTS: PROGENITOR MASSES, BOLOMETRIC CORRECTIONS, AND AGES

4.1. *Progenitor Masses: Does Metallicity Matter?*

In Table 5, we list the progenitor masses of the Milky Way W-R stars in our sample, adopting the cluster turnoffs from Table 4. Values for stars not strictly coeval are included in parentheses. We do not include any entries for the two clusters we consider to be noncoeval, Tr 27 and NGC 6871. We illustrate our results in Figure 4, where we include our data from the LMC and SMC from Paper I.

We see immediately that the progenitor of W-R stars span a large range in the Milky Way. *Wolf-Rayet stars in the Milky Way are found in coeval clusters that have turnoff masses as low as 20 $M_{\odot}$, and as high as or higher than 120 $M_{\odot}$.*

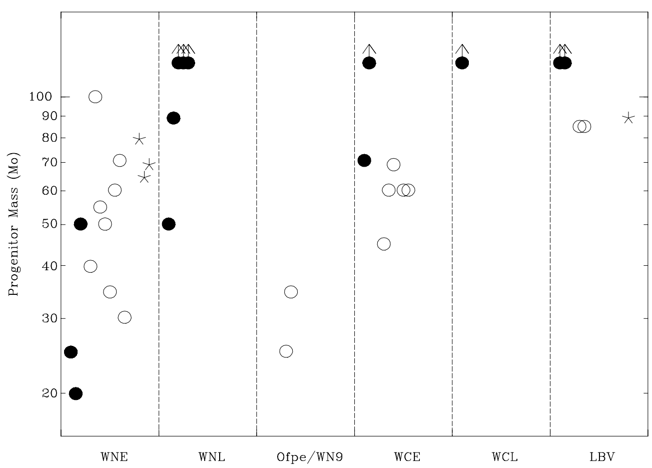

FIG. 4.—Progenitor masses of evolved stars for the Milky Way (*filled circles*), the LMC (*open circles*), and the SMC (*stars*).

Previous estimates of the "minimum mass" to become a W-R star have tended to be around 40 $M_{\odot}$ (Conti et al. 1983). The fact that we have two clusters, Ru 44 and Ma 50, both with turnoff masses of 20–25 $M_{\odot}$, both of which are highly coeval, and both of which contain W-R stars suggests otherwise. This result is one we could have anticipated from Paper I, where we found that at the lowest metallicity (SMC; $Z = 0.005$) the lowest mass progenitors of W-R stars were over 70 $M_{\odot}$. In the LMC ($Z = 0.008$), progenitor masses ranged as low as 30 $M_{\odot}$. It is perhaps then not surprising to find 20–25 $M_{\odot}$ stars in the Milky Way ($Z = 0.018$) becoming W-R stars.

In the LMC, we found that the progenitor masses of the WNE stars covered a very wide range. The data for the Milky Way, scant as they are, suggest much the same (Fig. 4), as Berk 86 has a very high turnoff mass. On the other hand, its W-R member, V444 Cyg, is a relatively short period binary, and Roche lobe–induced mass loss may have affected its evolution and current spectral type. It is hard to conclude whether the WNE stage has an evolutionary significance in the Milky Way, other than to say that both of the clusters that contain the lowest turnoff masses contain WNE stars.

It seems inescapable, though, that the WNL class, and in particular the WN7 stars, are in fact descendants of the highest mass stars. The "WNL" section of Figure 4 includes the 50 $M_{\odot}$ WN6 star MR 55; the other four stars are all of WN7 class. Both the models and other arguments suggest that *some* of these H-rich W-R stars may actually still be core hydrogen burning objects (see discussion in Conti et al. 1995). We argue below (§ 4.3) that in any event these stars are *evolved*; i.e., they are not simply very high mass stars with strong stellar winds, as was found in NGC 3603 and R136 (Massey & Hunter 1998).

All three of the WC stars in our sample are found in clusters with high turnoff masses. While the data are scant, this suggests that the 20 $M_{\odot}$ WNE stars may not become WC stars at Milky Way metallicities. In the Magellanic

TABLE 5

PROGENITOR MASSES, BOLOMETRIC CORRECTIONS, AND AGES

Star	Cluster	Spectral Type	Progenitor Mass ($M_{\odot}$)	M_V	M_{bol} (TAMS)	Bolometric Correction: No Evolution	Bolometric Correction: Max. Evolution	Age (Myr)
WNE:								
HD 65865	Ru 44	WN4.5	25	−4.2	−8.5	< −4.3	< −4.5	2.1
MR 120	Ma 50	WN4.5	20	…	…	…	…	7.4
V444 Cyg	Berk 86	WN5 (+O6)	50	…	…	…	…	2.5
WNL:								
MR 55	Pis 20	WN6	(50)	−5.1	(−9.9)	(< −4.8)	(< −2.4)	(3.6)
HD 93131	Cr 228	WN7	90	−6.8	−10.8	< −4.0	< −0.1	2.1
HD 93162	Tr 14/16	WN7 + abs	>120	−5.9	< −11.2	< −5.3	< −2.3	0.9
WR 87	C1715−387	WN7	>120	−7.6	< −11.2	< −3.6	< −0.6	1.1
AS 223	C1715−387	WN7	>120	−6.7	< −11.2	< −4.5	< −1.5	1.1
WCE:								
ST 3	Berk 87	WC5p (WO2)	70	−3.8	−10.5	< −6.7	< −3.0	3.2
MR 110	Cyg OB2	WC5	(>120)	…	…	…	…	(1.4)
WCL:								
HD 157504	Pis 24	WC7	>120	−6.4	< −11.2	< −4.8	< −1.8	0.7
LBV:								
η Car	Tr 14/16	LBV	>120	…	…	…	…	0.9
VI Cyg No. 12	Cyg OB2	LBV candidate	(>120)	…	…	…	…	(1.4)

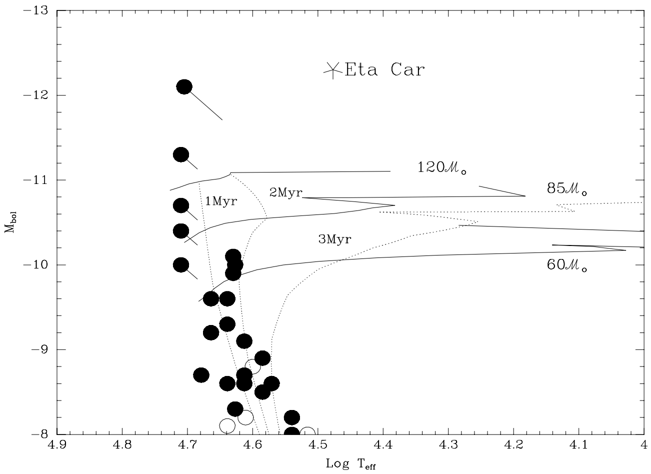

FIG. 5.—Uppermost section of the H-R diagram of Tr 14. The five hottest stars are all of type O3, and they are plotted using the values of Vacca, Garmany, & Shull (1996); the diagonal lines show where the stars would lie using the cooler scale of Chlebowski & Garmany (1991). The filled circles are stars with spectral types; the open circles are stars with only photometry, and the location of η Car is shown. The solid lines show the $Z = 0.020$ evolutionary tracks of Schaller et al. (1992), and the dotted lines show the isochrones completed for 1, 2, and 3 Myr.

Clouds we did find some WC stars in clusters with turnoff masses of 45 $M_\odot$. There is some overlap in the data (as shown in Fig. 4), and such a difference would be hard to understand on the basis of stellar evolution; perhaps we are simply seeing the effects of small number statistics.

Finally, both the LBV star η Car and the "LBV candidate" VI Cyg No. 12 (Massey & Thompson 1991) are found in clusters with the highest turnoffs. This was also true for *all* of the LBVs, and LBV candidates, in the Magellanic Clouds (Fig. 4). We consider this strong evidence that LBVs are a normal stage in the evolution of the most massive stars.

4.2. *Bolometric Corrections*

Let us turn briefly now to the bolometric corrections (BCs). Our assumptions here are the same as in Paper I, namely, that we can place limits on the bolometric corrections for Wolf-Rayet stars by assuming that the W-R star is at least as luminous (bolometrically) as the highest mass cluster star, and then comparing this with the absolute visual magnitude of the W-R star, following in the footsteps of Humphreys et al. (1985) and Smith et al. (1994).

However, in the Magellanic Clouds the amount of (bolometric) luminosity change during the W-R phase was quite modest according to the models, -1.0 to $+0.5$ mag, relative to the luminosity at the end of core H burning. Here, with the far greater mass-loss rates that characterize the Milky Way, the evolutionary models predict very large luminosity evolution. This is dramatically illustrated in Figures 5–7 of Schaller et al. (1992). At Milky Way metallicities, the models predict a change of 4 mag during the He-burning phase for stars of 85 $M_\odot$! For lower luminosities the change is more modest, and it becomes negligible below 25 $M_\odot$. Nevertheless, we can make some useful comparisons.

In Paper I, we found that the BCs of the WNE stars ranged from less than about -4 for the lowest masses to -7 for the highest masses. Here we have only one WN star without a companion confusing the photometry, and the BC is consistent with what we see for the Magellanic Cloud WNE stars, less than about -4.2 for the low-mass HD 65865.

Crowther, Hillier, & Smith (1995) analyzed nine Galactic WNL stars, including two in our sample. Model analysis suggests BCs of -3.1 for HD 93131 and -3.0 for HD 93162. For these two stars, we find respectively BCs of less than about -4.1 and -5.4, with no evolution, and less than about -0.6 and -1.5 with maximum evolution. We can at least say that there is no conflict with the "standard model" calculations, in accord with our findings in Paper I that there was good agreement between the models and this empirical method of finding the BCs.

4.3. *Ages*

One of the most glaring facts to emerge from Table 5 is that many of the evolved stars have ages of ~ 1 Myr, if they are indeed coeval with their associated clusters. Because the mass-luminosity relation is quite shallow for high-mass stars, the H-burning lifetime is not a steep function of mass. A 120 $M_\odot$ star will have an H-burning lifetime of 2.3 Myr according to the Schaller et al. (1992) models; it is not clear whether the 1 Myr lifetime is consistent with *any* star having evolved past core H burning. What then should we make of these "evolved" stars?

Could the ages be wrong? All four of the youngest regions contain O3 stars, and as Massey & Hunter (1998) discuss, there is both a "hot" and a "cool" temperature scale for O3 stars, and we have adopted the "hot" scale (see, e.g., Vacca, Garmany, & Shull 1996). This will lead to younger ages than had we adopted the cooler scale, but inspection of Table 3 shows that this is not a significant factor. For instance, although Tr 14/16 contain many O3 stars, we would infer the same age of the region were we to use the multitude of O5–O6 stars present. However, in Cyg OB2 we reach a somewhat different conclusion, as here the O3 star does give a slightly younger age ($\lesssim 1$ Myr) than the other massive stars (1.5 Myr). Since the O3 class is degenerate, accurate placement of these stars is not possible without detailed modeling, but in general it appears that the ages we have derived are reliable.

Alternatively, we need to ask whether these "evolved" objects are in fact evolved. In both NGC 3603 and R136 there are peculiar W-R stars that Massey & Hunter (1998) argue are simply "super-Of" stars—stars that are still H-burning and relatively unevolved, but whose extremely high luminosities and stellar winds result in Wolf-Rayet emission features. However, the NGC 3603 and R136 W-R stars are clearly unusual: despite being of "early" type (WN4.5) they have H-rich envelopes and very high absolute magnitudes. However, these properties are normally what we associate with WN7 stars: H-rich envelopes and high absolute visual magnitudes. We remind the reader that the Crowther (2000) study suggests that different WN spectral subclasses result from metallicity. Perhaps the "WN7" class in the Milky Way are extreme examples of Of stars, analogs of the very high mass objects found in NGC 3603 and R136 (with similar young ages). One could imagine that such objects, still showing H, have strong emission spectra because of high mass-loss rates, and enhanced composition at the surface due to mixing from the core.

However, we are dubious of this explanation for one outstanding reason: η Car. Although described as an "atypical prototype" of an LBV, it is very hard to imagine that this peculiar object is still in a normal, H-burning stage. The alternative suggestion that η Car is a binary (Damineli, Conti, & Lopes 1997) has been refuted by improved data (Davidson et al. 2000).

Let us consider whether or not η Car is coeval with its surrounding cluster. Although the spectral energy distributions of LBVs are poorly understood (Humphreys & Davidson 1994), η Car is surrounded by dust, which has conveniently reprocessed its UV radiation into IR, making its bolometric luminosity relatively well known: the object is one of the brightest 20 μm sources in the sky. Westphal & Neugebauer (1969) estimate its bolometric luminosity as -13.6; Davidson et al. (1986) find -12.3; we have corrected both values to our 3.1 kpc distance. We show the upper part of the H-R diagram in Figure 5, where we have plotted η Car using its more conservative luminosity, and using the 30,000 K effective temperature adopted by Davidson et al. This diagram certainly implies that η Car is coeval with the Tr 14/16 cluster. Furthermore, this also suggests that we are not simply looking at a few very massive stars that happen to have formed first. Without evolutionary tracks that extend to higher masses, it is hard to assign an exact age, but η Car's location in the H-R diagram is consistent with its simply being slightly higher mass than the highest mass O3 star, and evolved.

5. SUMMARY

We have conducted a study of 12 Galactic clusters containing Wolf-Rayet stars and LBVs, obtaining new spectroscopic data for eight. Of these, all but two prove to be highly coeval. We reach the following conclusions:

1. Wolf-Rayet stars in the Milky Way are found in clusters containing a large range of turnoff masses. The data suggest that at the metallicity that characterizes the Milky Way, some early-type WN Wolf-Rayet stars come from progenitors with masses as low as 20–25 $M_{\odot}$.
2. The WNE stars may come from a large range in masses, as they do in the Magellanic Clouds (Paper I), but this result is uncertain, as the one high-mass WNE star in our sample is a member of a close binary, V444 Cyg.
3. WN7 stars are found only in clusters with the highest masses. The youngest of these are only 1 Myr old. Although these could still be H-burning objects, "guilt by association" suggests that these are in fact evolved massive stars, as the youngest region also contains the LBV η Car, thought to be an evolved object.
4. For itself, η Car is found to be highly coeval with the rest of the Tr 14/16 complex, despite the region's young age. It and the LBV candidate VI Cyg No. 12 are found in clusters with the highest masses. This is identical to what we found for the Magellanic Clouds in Paper I and argues strongly that LBVs are a normal stage in the evolution of the most massive stars.
5. The Galactic WC stars are found in clusters with turnoff masses greater than 70 $M_{\odot}$. In the Magellanic Clouds, we find WC stars occurring in clusters with masses as low as 45 $M_{\odot}$. We argued in Paper I that most WN stars thus evolve to WC stars. The data for the Milky Way might suggest that only the more massive stars become WC stars, but the sample size in the Milky Way is small (three WC stars in three clusters) and additional data are needed.
6. The BCs of Galactic W-R stars are hard to determine using the cluster turnoff methods, as considerable luminosity evolution is expected at the higher mass-loss rates that characterize the Milky Way's luminous stars. The data are at least consistent with the "standard model" of Hillier (1987, 1990) as applied to two of the stars in our sample (Crowther et al. 1995). In Paper I, we concluded that there was excellent agreement, with the BCs of early WN and WC stars found to be extreme (approximately -6 mag).

We note that much recent work has established the need to extend the theoretical evolutionary tracks to masses higher than 120 $M_{\odot}$. Stars with masses estimated to be as high as 160 $M_{\odot}$ have been found in the R136 cluster (Massey & Hunter 1998), and the Galactic clusters Tr 14/16, C1715−387, Pis 24, and Cyg OB2 all contain stars whose luminosities place them above the highest evolutionary track computed by the Geneva group (120 $M_{\odot}$). Future observational work is needed to extend the H-R diagrams of these and other Galactic clusters, and to investigate other coeval regions in the Milky Way and nearby galaxies that can be used to extend these studies.

The majority of the data presented here were obtained during a very pleasant observing run at Cerro Tololo Inter-American Observatory, and we thank its excellent support staff. Additional spectra were obtained during Director's Discretionary Time on Kitt Peak, and we thank Richard Green for making this time available. This paper was prepared while P. M. was on sabbatical at Northern Arizona University, and we thank Barry Lutz for making an office available and for other hospitality. E. W. was supported through the Research Experiences for Undergraduates program, which was supported by the National Science Foundation under grant 94-23921 to Northern Arizona University. Useful comments on a draft of the manuscript were provided by Deidre Hunter and Nolan Walborn.

REFERENCES

Abbott, D. C. 1982, ApJ, 259, 282
Armandroff, T. E., & Massey, P. 1991, AJ, 102, 927
Bakker, R., & Thé, P. S. 1983, A&AS, 52, 27
Barbá, R. H., Niemela, V. S., Baume, G., & Vázquez, R. A. 1995, ApJ, 446, L23
Baume, G., Vázquez, R. A., & Feinstein, A. 1999, A&AS, 137, 233
Bohannan, B., & Crowther, P. A. 1999, ApJ, 511, 374
Bohannan, B., & Walborn, N. R. 1989, PASP, 101, 520
Burkholder, V., Massey, P., & Morrell, N. 1997, ApJ, 490, 328
Cherepashchuk, A. M., Koenigsberger, G., Marchenko, S. V., & Moffat, A. F. J. 1995, A&A, 293, 142
Chlebowski, T., & Garmany, C. D. 1991, ApJ, 368, 241
Conti, P. S. 1976, Mem. Soc. R. Sci. Liège, 9, 193
Conti, P. S. 1982, in IAU Symp. 99, Wolf-Rayet Stars: Observations, Physics, Evolution, ed. C. W. H. de Loore & A. J. Willis (Dordrecht: Reidel), 3
Conti, P. S., Garmany, C. D., de Loore, C., & Vanbeveren, D. 1983, ApJ, 274, 302
Conti, P. S., Hanson, M. M., Morris, P. W., Willis, A. J., & Fossey, S. J. 1995, ApJ, 445, L35
Conti, P. S., & Massey, P. 1989, ApJ, 337, 251
Conti, P. S., & Vacca, W. D. 1990, AJ, 100, 431
Crampton, D. 1971, AJ, 76, 260
———. 1975, PASP, 87, 523
Crowther, P. A. 2000, A&A, 356, 191
Crowther, P. A., & Dessart, L. 1998, MNRAS, 296, 622
Crowther, P. A., Hillier, D. J., & Smith, L. J. 1995, A&A, 293, 403

Damineli, A., Conti, P. S., & Lopes, D. F. 1997, NewA, 2, 107
Davidson, K., Dufour, R. J., Walborn, N. R., & Gull, T. R. 1986, ApJ, 305, 867
Davidson, K., Ishibashi, K., Gull, T. R., Humphreys, R. M., & Smith, N. 2000, ApJ, 530, L107
DeGioia-Eastwood, K., Throop, H., Walker, G., & Cudworth, K. M. 2001, ApJ, in press
de Koter, A., Heap, S. R., & Hubeny, I. 1997, ApJ, 477, 792
Drissen, L., Moffat, A. F. J., Walborn, N. R., & Shara, M. M. 1995, AJ, 110, 2235
Esteban, D., & Peimbert, M. 1995, in The Fifth Mexico-Texas Conference on Astrophysics, ed. M. Peña & S. Kurtz (Rev. Mexicana Astron. Astrofis. Ser. Conf. 3) (México D.F.: Inst. Astron., Univ. Nac. Autónoma México), 133
Feinstein, A., Marraco, H. G., & Forte, J. C. 1976, A&AS, 24, 389
FitzGerald, M. P. 1970, A&A, 4, 234
FitzGerald, M. P., & Moffat, A. F. J. 1976, A&A, 50, 149
Grubissich, C. 1965, Z. Astrophys., 60, 256
Havlen, R. J. 1976, A&A, 47, 193
Havlen, R. J., & Moffat, A. F. J. 1977, A&A, 58, 351
Herrero, A., Kudritzki, R.-P., Gabler, R., Vílchez, J. M., & Gabler, A. 1995, A&A, 297, 556
Hillenbrand, L. A., Massey, P., Strom, S. E., & Merrill, K. M. 1993, AJ, 106, 1906
Hillier, D. J. 1987, ApJS, 63, 947
———. 1990, A&A, 231, 116
Humphreys, R. M., & Davidson, K. 1994, PASP, 106, 1025
Humphreys, R. M., & McElroy, D. B. 1984, ApJ, 284, 565
Humphreys, R. M., Nichols, M., & Massey, P. 1985, AJ, 90, 101
Imhoff, C. L., & Keenan, P. C. 1976, ApJ, 205, 455
Kudritzki, R.-P. 1980, A&A, 85, 174
Levato, H., & Malaroda, S. 1981, PASP, 93, 714
Lortet, M.-C., Testor, G., & Niemela, V. 1984, A&A, 140, 24
Lundström, I., & Stenholm, B. 1984, A&AS, 58, 163
Maeder, A. 1997, A&A, 321, 134
———. 1999, in IAU Symp. 193, Wolf-Rayet Phenomena in Massive Stars and Starburst Galaxies, ed. K. A. van der Hucht, G. Koenigsberger, & P. R. J. Eenens (San Francisco: ASP), 177
Maeder, A., & Conti, P. S. 1994, ARA&A, 32, 227
Markarian, B. E. 1951, Soobshch. Byurakan Obs., 9, 1
Massey, P. 1996, in Wolf-Rayet Stars in the Framework of Stellar Evolution, ed. J. M. Vreux, A. Detal, D. Fraipont-Caro, D. Gosset, & G. Rauw (Liège: Inst. d'Astrophys., Univ. Liège), 361
———. 1998a, in Stellar Astrophysics for the Local Group, ed. A. Aparicio, A. Herrero, & F. Sánchez (Cambridge: Cambridge Univ. Press), 95
———. 1998b, ApJ, 501, 153
———. 1998c, in ASP Conf. Ser. 142, The Stellar Initial Mass Function, ed. G. Gilmore & D. Howell (San Francisco, ASP), 17
Massey, P., Bianchi, L., Hutchings, J. B., & Stecher, T. P. 1996, ApJ, 469, 629
Massey, P., & Conti, P. 1980, ApJ, 242, 638
Massey, P., & Hunter, D. A. 1998, ApJ, 493, 180
Massey, P., & Johnson, J. 1993, AJ, 105, 980
Massey, P., Johnson, K. E., & DeGioia-Eastwood, K. 1995a, ApJ, 454, 151
Massey, P., & Johnson, O. 1998, ApJ, 505, 793
Massey, P., Lang, C. C., DeGioia-Eastwood, K., & Garmany, C. D. 1995b, ApJ, 438, 188
Massey, P., & Thompson, A. B. 1991, AJ, 101, 1408
Massey, P., Waterhouse, E., & DeGioia-Eastwood, K. 2000, AJ, 119, 2214
McCarthy, C. C., & Miller, E. W. 1974, AJ, 79, 1396
Meynet, G., Maeder, A., Schaller, G., Schaerer, D., & Charbonnel, C. 1994, A&AS, 103, 97
Moffat, A. F. J. 1982, in IAU Symp. 99, Wolf-Rayet Stars: Observations, Physics, Evolution, ed. C. W. H. de Loore & A. J. Willis (Dordrecht: Reidel), 515
Moffat, A. F. J., & FitzGerald, M. P. 1974, A&A, 34, 291
Moffat, A. F. J., FitzGerald, M. P., & Jackson, P. D. 1977, ApJ, 215, 106
Moffat, A. F. J., & Vogt, N. 1973, A&AS, 10, 135
Neckel, T. 1978, A&A, 69, 51
Perry, C. L., Hill, G., & Christodoulou, D. M. 1991, A&AS, 90, 195
Reed, B. C., & FitzGerald, M. P. 1983, MNRAS, 205, 241
Russell, S. C., & Dopita, M. A. 1990, ApJS, 74, 93
Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, A&AS, 96, 269
Schild, H., & Maeder, A. 1984, A&A, 136, 237
Simon, K. P., Jonas, G., Kudritzki, R.-P., & Rahe, J. 1983, A&A, 125, 34
Smith, L. F. 1968, MNRAS, 141, 317
Smith, L. F., Meynet, G., & Mermilliod, J.-C. 1994, A&A, 287, 835
Sung, H., Bessell, M. S., & Lee, S.-W. 1998, AJ, 115, 734
Tapia, M., Roth, M., Marraco, H., & Ruiz, M. T. 1988, MNRAS, 232, 661
Thé, P. S., Arens, M., & van der Hucht, K. A. 1982, Astrophys. Lett., 22, 109
Thé, P. S., & Stokes, N. 1970, A&A, 5, 298
Turner, D. G. 1981, AJ, 86, 222
Turner, D. G., & Forbes, D. 1982, PASP, 94, 789
Turner, D. G., & Moffat, A. F. J. 1980, MNRAS, 192, 283
Turner, D. G., Moffat, A. F. J., Lamontagne, R., & Maitzen, H. M. 1983, AJ, 88, 1199
Vacca, W. D., Garmany, C. D., & Shull, J. M. 1996, ApJ, 460, 914
van der Hucht, K. A., Conti, P. S., Lundström, I., & Stenholm, B. 1981, Space Sci. Rev., 28, 227
Vázquez, R. A., & Feinstein, A. 1990, Rev. Mexicana Astron. Astrofis., 21, 346
Vijapurkar, J., & Drilling, J. S. 1993, ApJS, 89, 293
Walborn, N. R. 1971, ApJ, 167, L31
———. 1973a, ApJ, 179, 517
———. 1973b, ApJ, 180, L35
———. 1982, AJ, 87, 1300
———. 1994, in ASP Conf. Ser. 60, The MK Process at 50 Years, ed. C. J. Corbally, R. O. Gray, & R. F. Garrison (San Francisco: ASP), 84
Walborn, N. R., & Fitzpatrick, E. L. 1990, PASP, 102, 379
———. 2000, PASP, 112, 50
Westphal, J. A., & Neugebauer, G. 1969, ApJ, 156, L45
Willis, A. J., Schild, H., & Smith, L. J. 1992, A&A, 261, 419